

PB-227 364

OIL SPILL SURVEILLANCE SYSTEM STUDY

Don Mohr, et al

Texas Instruments, Incorporated

Prepared for:

Environmental Protection Agency

May 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Monitoring, Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

**SELECTED WATER
RESOURCES ABSTRACTS
INPUT TRANSACTION FORM**

1. Report No. 2.

PB 227 364

W

4. Title

OIL SPILL SURVEILLANCE SYSTEM STUDY

5. Report Date

6.

8. Performing Organization
Report No.

7. Author(s)

Don Mohr, Kent McCormack, Gary Brewster, G. Fournier

10. Project No.

9. Organization

**Texas Instruments Incorporated
Post Office Box 6015
Dallas, Texas 75222**

15080HGP

11. Contract/Grant No.
68-01-0150

12. Sponsoring Organization

13. Type of Report and
Period Covered

15. Supplementary Notes

Environmental Protection Agency Report No. EPA-R2-73-215, May 1973

16. Abstract

Tests of active and passive infrared sensor systems were conducted to determine the ability of these systems to detect petroleum oil on water. Since there are temperature and emissivity differences between oil and water it was expected that these systems would have applications for real time detection, alarm, monitoring, and recording of oil spilled or discharged in harbors, lakes, rivers, estuaries and coastal waters.

Both sensors had distinct advantages. The active sensor provided absolute oil spill detection for ranges to 300 feet. The passive sensor makes possible oil volume determination, areal coverage, and probable oil detection for ranges to 1000 feet.

Since both sensors have distinct advantages, a combination of the two is recommended.

17a. Descriptors

**Oily wastes, Pollutant identification, Infrared radiation,
Instrumentation, Remote sensing.**

17b. Identifiers

Spill detection, Active infrared, Passive infrared.

Reproduced by
**NATIONAL TECHNICAL
INFORMATION SERVICE**
U S Department of Commerce
Springfield VA 22151

17c. COWRR Field & Group

18. Availability

19. Security Class.
(Report)

21. No. of
Pages

Send To:

20. Security Class.
(Page)

22. Price

**WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240**

Abstractor **Don Mohr**

Institution **Texas Instruments Incorporated**

OIL SPILL SURVEILLANCE

SYSTEM STUDY

by

Don Mohr
Kent McCormack
Gary Brewster
Gerald Fournier

Contract No. 68-01-0150
Project 15080 HOP

Project Officer

John E. Riley
Office of Air and Water Programs
Environmental Protection Agency
Washington, D.C. 20460

Prepared for
OFFICE OF RESEARCH AND MONITORING
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

EPA Review Notice

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

Test studies of active and passive infrared sensor systems were conducted to determine the ability of these systems to detect petroleum oil on the water's surface. Since there are temperature, as well as emissivity differences between oil and water, it was expected that these systems might have applications for real time detection, alarm, monitoring, and recording of oil spilled or discharged in harbors, lakes, rivers, estuaries, and near shore coastal waters.

The test results indicate that both sensor systems have distinct advantages in oil spill surveillance applications. The active sensor provides absolute oil spill detection, for ranges to 300 feet that is not affected by the time of day, weather, or water surface conditions. The passive sensor makes possible oil volume determination, areal coverage, and probable oil detection for ranges to 1000 feet.

Since both evaluated sensor systems have distinct and equally important features, a combination active and passive sensor system would provide the best surveillance for oil spill applications. Two combination system designs are described in this report.

This report was submitted in fulfillment of Project Number 15080 HOP, Contract 68-01-0150, under the sponsorship of the Environmental Protection Agency.

Contents

<u>Section</u>		<u>Page</u>
I	Conclusions	1
II	Recommendations	3
III	Introduction	5
IV	Demonstration Program	7
V	Demonstration System, Active Sensor	17
VI	Demonstration System, Passive Sensor	59
VII	Test Results, Active Sensor	67
VIII	Test Results, Passive Sensor	113
IX	System Concepts, Active Sensor	155
X	System Concepts, Passive Sensor	173
XI	Total System Approach	203
XII	Acknowledgements	209
XIII	References	211
XIV	Glossary	213

Figures

<u>No.</u>		<u>Page</u>
1	Test Site Tower	8
2	Test Site Building	9
3	Active Sensor Test Equipment	10
4	Passive Sensor Test Equipment	10
5	Atmospheric Transmission	12
6	Active Sensor Test Setup	14
7	Active Sensor Recording Equipment	15
8	Passive Sensor Test Setup	15
9	Passive Sensor Monitoring Equipment	16
10	Galveston Test Site	16
11	Active Sensor, MOD 1	17
12	Active Sensor, MOD 2	18
13	Active Sensor, MOD 3	18
14	Spectral Reflectance of Water in the Infrared Region for Natural Polarization and Selected Angles of View*	20
15	Absorption Coefficient and Normal Reflectivity of Pure Water	23
16	Transmission of a 1000-Foot Horizontal Air Path at Sea Level, 5.7 mm Precipitable Water at 79°F Temperature	25
17	Transmission Data of Typical Crude Oil	26
18	Postulated Shape and Location of Normal Reflectance and Absorption Coefficients of Oil Relative to Those of Water	27
19	Optical Schematic of Active Infrared Oil Detection System, MOD 1	28
20	Block Diagram of Processing Circuitry	30
21	Probability that Sea Surface Slope is Less than or Equal to β versus $\beta\beta$	33
22	Slope Probability Density Versus β	34
23	Relative Flux Output Versus Input Energy for Pulsed Xenon Lamp	37

Figures (Continued)

<u>No.</u>		<u>Page</u>
24	Lamp Life Versus Applied Voltage for a Tungsten Halogen Lamp	38
25	Emitted Power at 3.5 Microns as a Function of Lamp Voltage (Tungsten)	39
26	Current Versus Applied Voltage for a Tungsten Halogen Lamp	40
27	Number of Pulses Versus the Single Shot Explosion	42
28	Pulse Width Versus Pulse Energy for X-80 Lamp	44
29	Number of Flashes of an X-80 Xenon Lamp Versus the Signal-to-Noise Ratio for a Pulsed Detection System	45
30	Receiver Optics	46
31	Optic Plate Adjustment Curve	48
32	Measured Reflectance from Smooth Oil and Water Surfaces	50
33	Reflectance from a Smooth Oil Surface at Normal Incidence	51
34	Lamp Output Versus Wavelength	53
35	Signature Dependence On Signal-to-Noise Ratio	54
36	Multipurpose Infrared System	60
37	MIRS Optics and Electronics Packaging	60
38	MIRS Concept Diagram	61
39	System MTF	63
40	HgCdTe Relative Spectral Response	65
41	Spectral Response of MIRS Optics	65
42	MOD 1 Mounted at 30 Feet Overlooking Body of Water	68
43	Example of Wave Probe Output	69

Figures (Continued)

<u>No.</u>		<u>Page</u>
44	Example of MOD 1 Data at 30 Feet (Sheet 1 of 7)	70
45	Example of MOD 1 Data with Fan Generated Waves (Sheet 1 of 7)	78
46	Geometry of Scan Data at 30 Feet	87
47	Water Target at $\phi = 2.9^\circ$, MOD 1 (Sheet 1 of 3)	88
48	Example of MOD 2 Test Data (Sheet 1 of 2)	91
49	Example of Water and Oil Discrimination	93
50	Test Scan Geometry	94
51	MOD 2 Signal Amplitude Versus Scan Angle for 30- and 50-Foot Heights	95
52	MOD 2 Signal Amplitude Versus Angle for Three Scan Directions	97
53	Angular Scan Limits of MODs 2 and 3	98
54	Modification Kit for MOD 3	100
55	MOD 3 Lab Data	101
56	Test Setup for MOD 3 at Gulf of Mexico Test Site	102
57	Typical Data from MOD 3 at 91 Feet	103
58	Predicted Operation with Sample and Hold Circuits	105
59	Pulse Sampling	106
60	Nighttime Data from MOD 2 at 91 Feet	107
61	Photograph of Wave Action	108
62	Amplitude Versus Tilt Angular for MOD 2 at 91 Feet, Tilt Angle 0° to 60°	109
63	Amplitude Versus Tilt Angle for MOD 2 at 91 Feet, Tilt Angle	110
64	Amplitude Versus Azimuth Angle, Tilt Angle 36°	111

Figures (Continued)

<u>No.</u>		<u>Page</u>
65	Water Profile After Breaking	112
66	Plastic Ring in Clean Water Before Adding Distillate	114
67	Navy Distillate Being Added to Water Inside Ring	114
68	Patches of Distillate Sheen	115
69	Distillate Being Stirred for Uniformity	115
70	Uniform Distillate Sheet	116
71	Uniform Distillate Sheen in Presence of Waves	116
72	Plastic Ring in Clean Water Before Adding Diesel Fuel Oil No. 2	117
73	Diesel Fuel Oil No. 2 Being Added to Water Inside Ring	117
74	Diesel Fuel Oil No. 2 Spread Evenly Inside Ring	118
75	Diesel Fuel Oil No. 2 Sheen in Presence of Waves	118
76	Plastic Ring in Clean Water Before Adding Diesel Fuel Oil No. 4	119
77	Diesel Fuel Oil No. 4 Being Added to Water Inside Ring	119
78	Patches of Diesel Fuel Oil No. 4 Sheen	120
79	Diesel Fuel Oil No. 4 Spread Evenly Inside Ring	120
80	Florida Crude Oil Being Added to Water Inside Ring	121
81	Florida Crude Oil Blown into Upper Right Corner by Wind	122
82	Small Portion of Florida Crude Oil Removed	122
83	Thick and Thin Spots of Florida Crude Oil Undispersed Over Entire Ring	123
84	Temporary Florida Crude Oil Sheen After Disturbance	123

Figures (Continued)

<u>No.</u>		<u>Page</u>
85	Lumps of Florida Crude Oil Coalescing Into Bright Spots	124
86	Florida Crude Oil Sheen After Removal of Most of Oil	124
87	Oil-Water Test Configuration	126
88	Temperatures of Water, Oil, and Air Over a Day's Time and the Corresponding Variations in Presentation	127
89	Florida Crude Oil on Water, 1800 Hours, 1/18/72	128
90	Florida Crude Oil on Water, 0600 Hours, 1/19/72	129
91	Florida Crude Oil on Water, 0630 Hours, 1/19/72	130
92	Florida Crude Oil on Water, 0650 Hours, 1/19/72	131
93	Florida Crude Oil on Water, 0700 Hours, 1/19/72	131
94	Florida Crude Oil on Water, 0730 Hours, 1/19/72	132
95	Florida Crude Oil on Water, 0900 Hours, 1/19/72	132
96	Florida Crude Oil on Water, 1100 Hours, 1/19/72	133
97	Florida Crude Oil on Water, Noon, 1/19/72	133
98	Some Florida Crude Oil Being Blown from Ring	134
99	Florida Crude Oil on Water, 1300 Hours, 1/19/72	135
100	Seaweed Sample	135
101	Plywood in Water	136
102	Plywood in Water After One Week	136
103	Oil Volume Test Setup	138
104	No Oil as Presented on Television display	140

Figures (Continued)

<u>No.</u>		<u>Page</u>
105	No Oil as Presented on Oscilloscope	141
106	2 Drops of Florida Crude Oil as Presented on Television Display	141
107	2 Drops of Florida Crude Oil as Presented on Oscilloscope	142
108	4 Drops of Florida Crude Oil as Presented on Television Display	142
109	4 Drops of Florida Crude Oil as Presented on Oscilloscope	143
110	8 Drops of Florida Crude Oil as Presented on Television Display	143
111	8 Drops of Florida Crude Oil as Presented on Oscilloscope	144
112	2 Cubic Centimeters of Florida Crude Oil as Presented on Television Display	144
113	2 Cubic Centimeters of Florida Crude Oil as Presented on Oscilloscope	145
114	5 Cubic Centimeters of Florida Crude Oil as Presented on Television Display	145
115	5 Cubic Centimeters of Florida Crude Oil as Presented on Oscilloscope	146
116	Apparent Temperature Versus Oil Thickness	147
117	Reflectivity and Emissivity of a Smooth Water Surface as a Function of Slant Angle	148
118	2 Ounces of Florida Crude Oil at 43 Degrees Slant Angle	148
119	2 Ounces of Florida Crude Oil at 60 Degrees Slant Angle	149
120	2 Ounces of Florida Crude Oil at 70 Degrees Slant Angle	149
121	Waves at a Slant Angle of 86 Degrees	150

Figures (Continued)

<u>No.</u>		<u>Page</u>
122	Galveston Bay as Seen From the Flagship Hotel	150
123	Galveston Bay at Slant Angle of 70 Degrees	151
124	Galveston Bay at Slant Angle of 70 Degrees	152
125	Signal Versus Scan Radius for MOD 2 a5 50-Foot Altitude	156
126	Signal Versus Scan Radius for MOD 2 at 100-Foot Altitude	157
127	Signal Versus Scan Radius for MOD 2 at 150 Foot Altitude	158
128	Signal Versus Scan Radius for MOD 3 at 50 Foot Altitude	159
129	Signal Versus Scan Radius for MOD 3 a5 100 Foot Altitude	160
130	Signal Versus Scan Radius for MOD 3 at 150 Foot Altitude	161
131	Concept for Arc and Area Scans	163
132	Gimbal System for Active Sensor	164
133	Scanner Block Diagram	166
134	Area Scan Concept and Display	167
135	Shipboard Application of Passive Scanner	175
136	Conceptual Line Scanner Approach to Oil Spill Surveillance System	176
137	RS-18 Outline Dimensions	178
138	Spectral Radiant Emittance Curves for Blackbodies at Several Absolute Temperatures	138
139	Liquid Transfer System and Passive Sensor Mounted on Tower	182
140	Transfer Piping System	183
141	Thermal Conductivity Linde Super Insulation	191
142	Schematic of Proposed Thermoelectric Cooler	195

Figures (Continued)

<u>No.</u>		<u>Page</u>
143	Input Power Versus Heatsink Temperature for a 0.05-Watt Load	196
144	Cold Side Temperature Versus Hot Side Temperature for 0.05-Watt	197
145	Oil Spill Imagery, 3- to 5.5-Microns	198
146	Schematic Representation of an Oil Separator Facility	204
147	Onshore Oil Separator Facility	205

TABLES

<u>No.</u>		<u>Page</u>
1	Characteristics of Circuit Elements	31
2	Transmitter	35
3	Characteristics of Tungsten Halogen Lamp	36
4	Characteristics of Xenon Lamps	41
5	Detectors	47
6	Computer Signatures Versus Wavelength	55
7	Atmospheric Effects	55
8	Signatures for Six Types of Oil and Water	56
9	Signatures for Various Types of Debris	56
10	Omitted	
11	Identification of Oil Types by Observed Characteristics	125
12	MOD 2 Coverage Tradeoff, PbSe Detectors at 243°K	169
13	MOD 2 Coverage Tradeoff, PbSe Detectors Cold Filtered at 193°K	169
14	MOD 3 Coverage Tradeoff, PbSe Detectors at 243°K	170
15	MOD 3 Coverage Tradeoff, PbSe Detectors Cold Filtered at 193°K	170
16	RS-18 Specifications	179
17	Dewar Characteristics	184
18	Basic Cooler Specifications	194
19	Oil Spill Sensor Application Matrix	206

SECTION I

CONCLUSIONS

1. The advantages and capabilities of the active infrared (IR) oil detection sensor are as follows:
 - a. Absolute distinction between petroleum oil and other naturally occurring substances such as kelp beds, salinity and temperature variations, and debris.
 - b. Suitable for scanning applications with coverage to 300 feet from the sensor.
 - c. Sensor sensitivity is capable of quick detection of an oil film on the water's surface.
 - d. Sensor output is suitable for transmitting an alarm.
 - e. Successful operation is independent of the time of day, weather, and water surface conditions.
 - f. Highly reliable and easy to maintain.
 - g. Relatively low initial cost and low operating cost.
 - h. Can be remotely installed on a fixed structure on land, or on an offshore platform.

The advantages and capabilities of the passive IR oil spill imagery system are as follows:

- a. Detection of thermal anomalies associated with oil spills.
- b. Suitable for scanning applications with coverage to 1000 feet from the system.
- c. System output is suitable for transmitting an alarm, making a film record, displaying on a monitor, and providing the possibility of oil spill volume determination.
- d. Successful operation is independent of weather and water surface conditions, and except for a short period of time at sunrise and sunset is independent of the time of day.
- e. Highly reliable and can be designed for easy maintainability.
- f. Relatively low initial cost and low operating cost.

SECTION I

CONCLUSIONS

- g. Can be installed on a fixed structure on land, on an offshore platform, or in an aircraft.

3. A combination of the active and passive systems can provide highly reliable oil spill surveillance.

SECTION II

RECOMMENDATIONS

The primary purpose of the evaluation phase of this study program was to determine the ability of existing active and passive sensors to detect oil spills. Each sensor demonstrated distinct advantages in oil spill surveillance applications. The active sensor provided absolute oil spill detection that was not affected by the time of day, weather, or water surface conditions. The passive sensor demonstrated the possibility of oil volume determination, ability for a real coverage, and long-range detection.

Since both evaluated sensors demonstrated distinct and equally important advantages, a combination active/passive sensor system is recommended for permanent oil spill surveillance applications. Two systems with these advantages are described in Sections IX, X, and XI.

Specifically there are several options available in most applications. The active sensor can be used as a staring system or a scanning system. It also has two recommended configurations in terms of range; Mode 2 and Mode 3, where Mode 3 is for extended range. The passive system also has two configurations; one is when the 8 to 14 microns wavelength region is used and the other is the 3 to 5 microns wavelength region. In either configuration the system can be used as a line scanner or as an areal framing system. The 3 to 5 microns system is the lower performance system but is simpler in terms of logistics. The following list of recommended sensors for reasonable applications is taken from Table 19.

- o Estuary: Active Mode 3 (Arc Scan W/Alarm) or Passive 3-5 microns (Line Scan W/Alarm)
- o Industrial Effluent: Active Mode 2 (Staring W/Alarm) or Passive 3-5 microns (Line Scan W/Alarm)
- o River/Bay Area (Tower): Passive 8-14 microns (Area Scan CRTI film) or Passive 3-5 microns (Area Scan CRTI film)
- o Drainage Channel $\leq 60^{(1)}$ Across: Active Mode 2 (Arc Scan W/Alarm)
- o Drainage Channel $\leq 150^{(1)}$ Across: Active Mode 3 (Arc Scan W/Alarm)
- o Drainage Channel $\geq 150^{(1)}$ Across: Passive 3-5 microns (Line Scan W/Alarm)
- o Offshore Drilling Platform: Active Mode 2 or Mode 3 (Arc Scan) or Passive 8-14 microns (Area Scan CRT 1 film)
- o Offshore Sperator Platform: Active Mode 2 (Staring or Arc Scan W/Alarm) or Passive 8-14 microns (Line Scan W/Alarm)

- 0 Dock Area: Active Mode 2 or Mode 3 (Arc Scan W/Alarm) or any of the Passive.

- 4

SECTION III

INTRODUCTION

The primary objective of this study program was to demonstrate a remote sensing oil spill surveillance system for real time detection, alarm, monitoring, and recording of oil spilled or discharged in harbors, lakes, rivers, estuaries, and near shore coastal waters. In addition, a complete thermal imagery and oil detection system, data analysis and oil spill alarm concepts were developed.

The demonstration phase of the study program was centered around two existing systems developed by Texas Instruments Incorporated; an active infrared (IR) sensor system for detection of oil on water and a passive IR imaging system for areal surveillance. The concept development phase was optimized by existing equipment using new techniques and sensors.

The active IR sensor system was designed explicitly to distinguish petroleum oil from water. Basically, the system emits a wide-band IR pulse and receives reflections at two narrow spectral bands to perform its function. The theory of operation is based on differences in the reflectance of water and oil at these narrow spectral bands (wavelengths).

The passive IR imaging system was developed by Texas Instruments Incorporated for the U.S. Army Night Vision Laboratory as a night weapon sight. This system receives IR radiation in the 8-to-14 micron spectral region. Since there are thermal, as well as emission differences between water and oil, oil can be detected by this system during the day or night. Although the passive IR imaging system cannot positively identify the presence of oil, it can complement the active IR sensor system by providing real-time areal surveillance with the added possibility of determining quantity of oil spilled.

Tests of the passive and active IR systems at the Texas Instruments and Galveston, Texas test sites during the demonstration phase have verified the capabilities of these systems to detect oil on the water's surface. Furthermore, practical limits on the variables of detection and observation have been determined. The following sections provide the results of these tests and the resultant system design concepts.

SECTION IV

DEMONSTRATION PROGRAM

The Oil Spill Surveillance System study consisted of two parts: (1) a demonstration program using existing sensors and (2) concept development. The specific requirements for the demonstration program were to test two different sensors to determine their feasibility and to demonstrate the application of these sensors to the detection and surveillance of oil spills on water surfaces. To accomplish this, both the active oil detection system and the passive surveillance system were simultaneously evaluated; hereafter, these systems shall be referred to as "active sensor" and "passive sensor", respectively.

Test Site

Texas Instruments approach was to construct a tower adjacent to a suitable body of water. The nature of the study required the creation of oil spills that could be contained and cleaned up.

A stock pond located on Texas Instruments property near Renner, Texas was chosen as the test site. This location offered one definite advantage over other lakes investigated. Since the lake was on private property and was self-contained (ie, fed into no streams or waterways) testing could be accomplished without ecological damage to property or wild life.

The pond used was approximately 300 feet by 200 feet. A tower was erected with platforms at the 50- and 30-foot levels. Figure 1 shows the location of the tower and a portion of the pond. A portable building, 20 feet by 10 feet, was moved to the location (Figure 2) to provide shelter for monitoring and recording equipment. Figure 3 shows some of the test equipment used to evaluate the active sensor, and Figure 4 shows test equipment used to evaluate the passive sensor. The Gulf of Mexico was used for long range tests.

Active Sensor Demonstration Program

The four objectives of the active sensor demonstration program were as follows:

1. Prove that the oil-water discrimination technique works on natural wave surfaces.

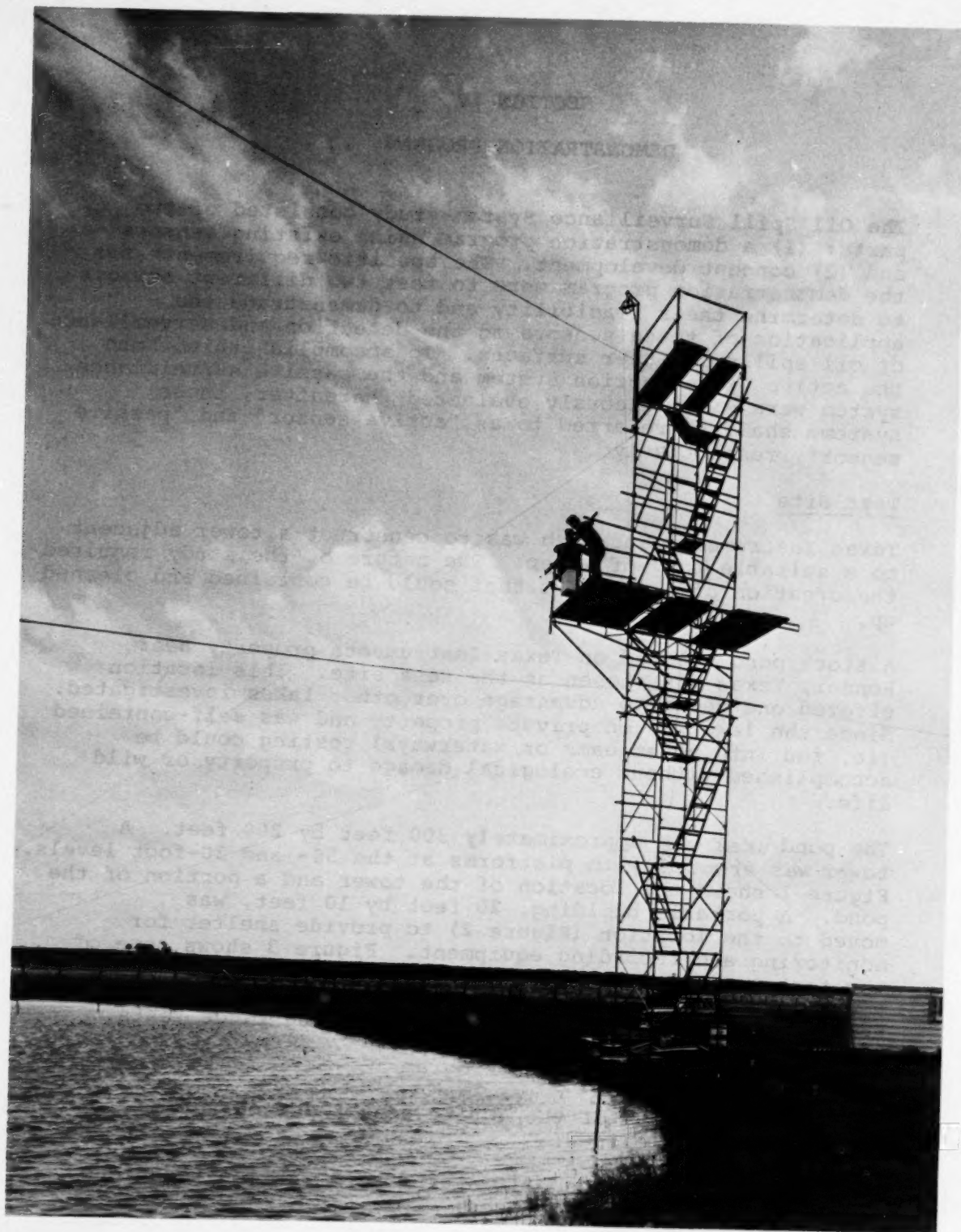


Figure 1. Test Site Tower

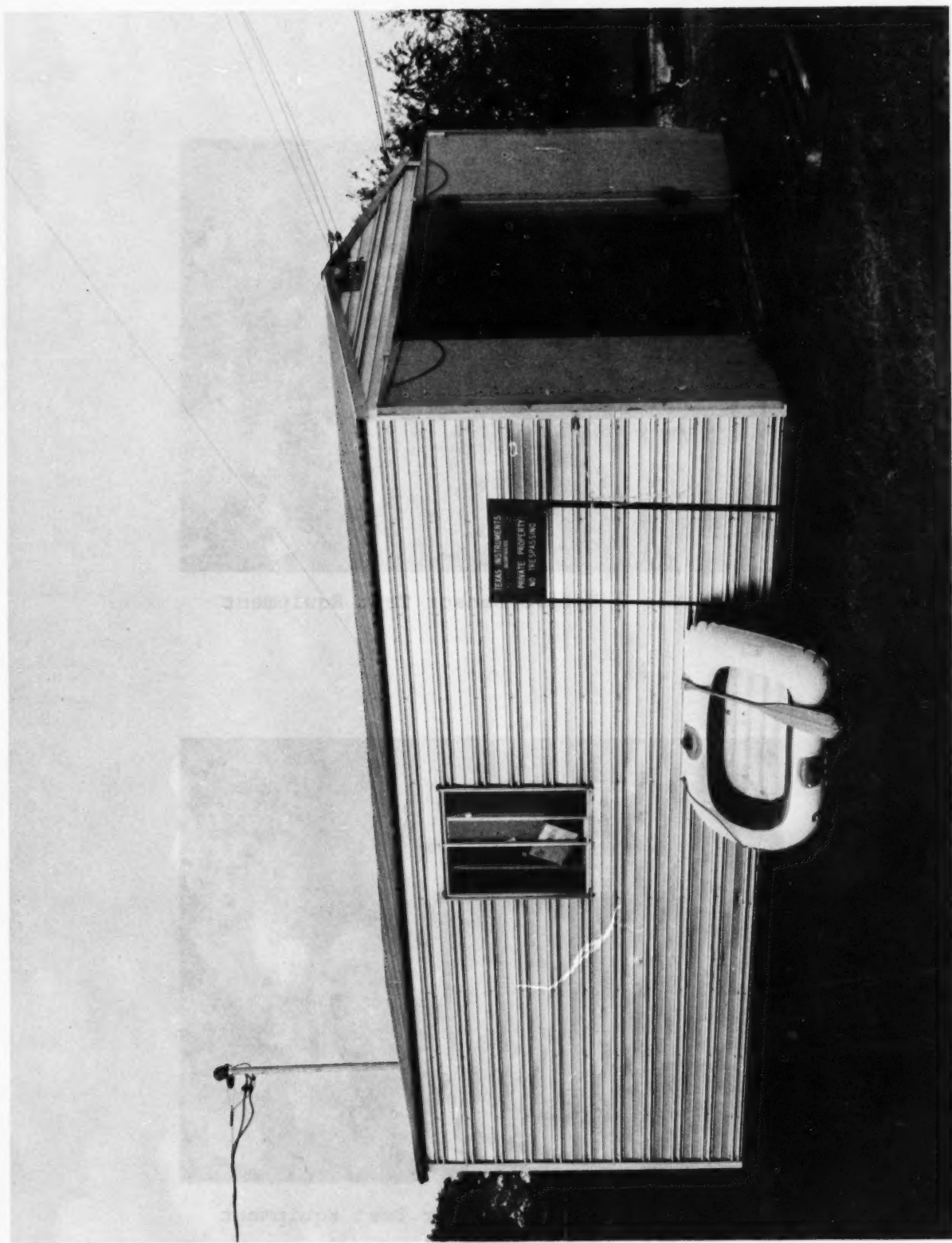


Figure 2. Test Site Building



Figure 3. Active Sensor Test Equipment



Figure 4. Passive Sensor Test Equipment

2. Prove that the technique works for a representative group of oils and that it does not cause a false alarm when common debris or marine growth is detected.

3. Establish and verify the range and angular scan capabilities of the technique using state-of-the-art components at a test site where wave action is unified.

4. Verify the range and angular scan performance of the instrumentation in a rough wave environment.

The results of this demonstration program has made possible the extrapolation of system performance for essentially any range and angle, when the surface condition is known. This program implemented three different forms of the active sensor. In each successive modification, the sensor had an increased signal-to-noise for greater range and/or angle.

Another important feature of the demonstration program was its conclusiveness. By the time the first three objectives had been achieved there was no need to perform the fourth phase of the program; ie, to spill oil. During the first three phases the independence of the signature from wave action was established. The only condition being that there was a sufficient signal-to-noise ratio as determined by the type of wave action, range, and angle. Hence, at the Gulf of Mexico test, there was no need to pollute the water, only to measure the signal-to-noise ratio for the above three parameters.

Other operational features of the system were not considered major because of the spectral region in which the system operates but were confirmed during the demonstration. Tests confirmed that active sensor operation is independent of time of day, humidity, rain and cloud cover.

During the course of the demonstration program the primary objectives was to make the conceptual system inexpensive in mass production, reliable, and low in maintenance by using state-of-the-art components, and experience gain from the test.

Passive Sensor Demonstration Program

The demonstration program for the passive sensor was developed to establish the practical limits of observation of oil spills using the 8- to 14-micron spectrum.

The choice of detector material used for the test sensor was based on the atmospheric effects on infrared energy and Wein's Displacement Law governing the wavelength of maximum

emission for targets at ambient temperature.

Figure 5 is a plot of percent transmission versus wavelength for horizontal paths of IR transmission. This curve shows that energy from 3 to 5 microns and from 8 to 14 microns is least attenuated by the atmosphere; therefore, a detector material that operates at one of these ranges of wavelengths provides optimum detection of oil.

The temperature of oil spills is approximately the temperature of water and water temperatures vary from 274°K to approximately 303°K (32°F to approximately 65°F).

Wein's displacement formula gives the relationship between temperature of a blackbody and the wavelength of its maximum thermal emission. Converting to degrees Kelvin:

$$T \lambda_{\text{max}} = 2900$$

(1)

where temperature (T) is in $^{\circ}\text{K}$ and the wavelength (λ_{max}) is measured in microns. From formula (1) and the temperature

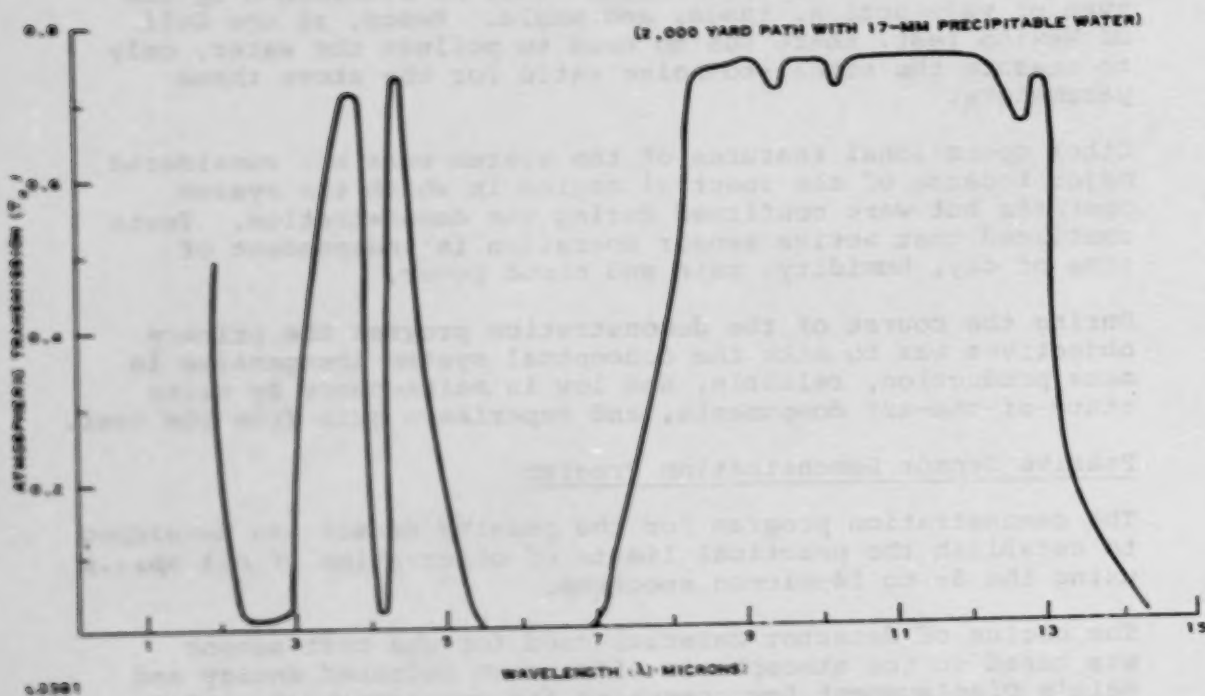


Figure 5 Atmospheric Transmission

limits of water, the range of λ for maximum emission is from 9.6 to 10.6 microns.

Thus, the choice of detectors in the 8- to 14-micron range is more appropriate for oil spill detection than the 3- to 5-micron range.

Tests performed encompassed basically three sets of variables: (1) environmental conditions, (2) oil film conditions, and (3) sensor configuration.

Environmental conditions included background (water) temperatures ranging from approximately 32°F to 65°F, and ambient (air) temperatures ranging from approximately 30°F to 85°F. Both day and night background conditions were examined as well as various sky backgrounds varying from clear to heavy overcast and rain. The second variable considered was oil film conditions. Various types of oil and thicknesses were observed during the demonstration program. Temperature signatures of equal amounts of several oil types, ranging from thin Navy Distillate to heavy crude oils, were recorded. Radiometric temperatures of oil with respect to water as a function of oil film thickness was also investigated. Both field and laboratory tests, with constant environmental conditions, were conducted to study the effects of thickness.

Various aspects of the sensor were continuously evaluated to determine the optimum configuration for maximum sensitivity and probability of detection. Various modulation levels of the light emitting diode array were examined. The closed-circuit TV data line was also investigated for optimization. The standard vidicon image tube was replaced with a Tivicon* tube which has peak sensitivity at the wavelength of the GaAsP diodes used in the passive sensor. Also, angles of observation variations were considered in sensor configuration. Vertical angles from 0 to 70 degrees were recorded.

Imagery from each of the tests was recorded on magnetic recording tape for later playback and analysis. Photographic prints were made of the imagery and many of these are presented in Section VIII of this report.

Long Range Tests

Long range and maximum angle of observation tests were not possible from the 50-foot tower at the Texas Instruments test site; therefore, both sensors were taken to Galveston, Texas. Testing in the Gulf of Mexico allowed both systems to be evaluated at a height and in an environment similar to those where an eventual operational system would be installed.

*Texas Instruments Incorporated Trademark

Selection of a site to conduct these tests was based on three desirable characteristics: (1) a minimum height of 100 feet, (2) heavy wave action (2-to 3-foot waves), and (3) the possibility of an occasional oil slick. Of the three desired test site characteristics, height and wave action were considered the most important. Since both systems had detected oil at 50 feet, the presence of an oil slick was not necessary. The Houston Ship Channel was considered because of the presence of oil but was rejected because it is usually calm. Several locations such as towers, bridges and oil rigs in various Texas cities were considered, but little encouragement was obtained in securing permission for use of those sites.

The location selected was the 7th floor of the Flagship Hotel in Galveston, Texas. Two adjacent rooms were rented and the equipment was mounted on the terraces overlooking the Gulf of Mexico from a height of 91 feet. The hotel is built on a wharf extending into the Gulf and is about 100 yards from the shore line.

During the test period, the Gulf had a continuous ripple of at least 3 inches in height. From 7:00 am to 3:00 pm on most days, the waves were approximately 2 feet high with a period of 15 feet and had a wave velocity of 5 seconds per cycle.

Photographs of the Galveston test site and equipment set up are shown in Figures 6 through 10. Figure 6 shows the active sensor mounted on the terrace and Figure 7 shows the associated recording equipment. The passive sensor mounted on the adjacent terrace is shown in Figure 8. The monitoring test setup for the passive sensor is shown in Figure 9. A side view of the hotel with the units mounted is shown in Figure 10.

The Galveston site test results are presented in Sections VII and VIII.



Figure 6. Active Sensor Test Setup



Figure 7. Active Sensor Recording Equipment



Figure 8. Passive Sensor Test Setup



Figure 9. Passive Sensor Monitoring Equipment



Figure 10. Galveston Test Site

SECTION V

DEMONSTRATION SYSTEM, ACTIVE SENSOR

The theory of operation of the active sensor is based on the difference in the reflectance of water and oil at two wavelengths in the 3- to 4-micron region. This spectral region was selected because of the presence of a universal hydrocarbon absorption band at 3.4 microns. The demonstration models tested on this program were developed in three phases herein designated MOD 1, MOD 2 and MOD 3. A photograph of MOD 1 is shown in Figure 11. This sensor is a laboratory unit that was implemented prior to this contract and modified for field operation at a 30-foot height. The components of MOD 2 are very similar to MOD 1 with the exception that refractive optics are used instead of reflective optics and a higher f/number was used to extend the range. A photograph of MOD 2 is shown in Figure 12. MOD 3, shown in Figure 13, uses a pulsed Xenon arc source rather than a 400-hertz modulated beam from a tungsten halogen/lamp.

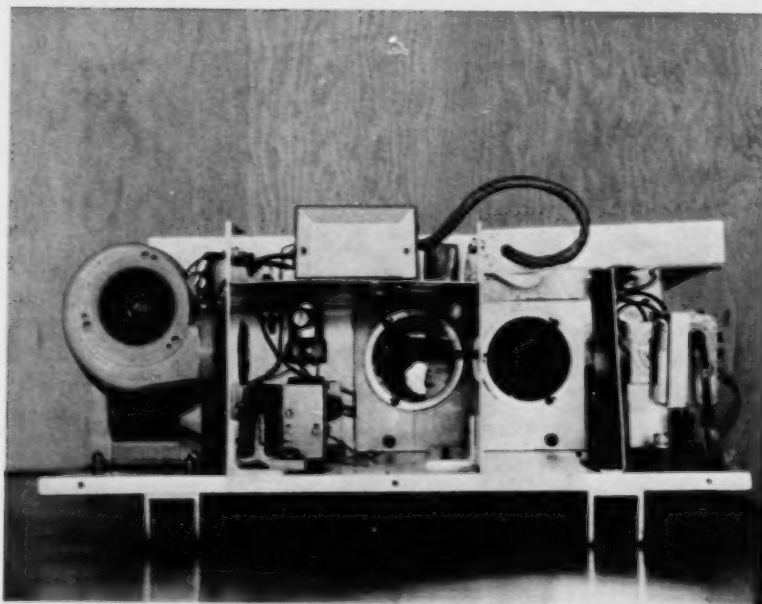


Figure 11. Active Sensor, MOD 1

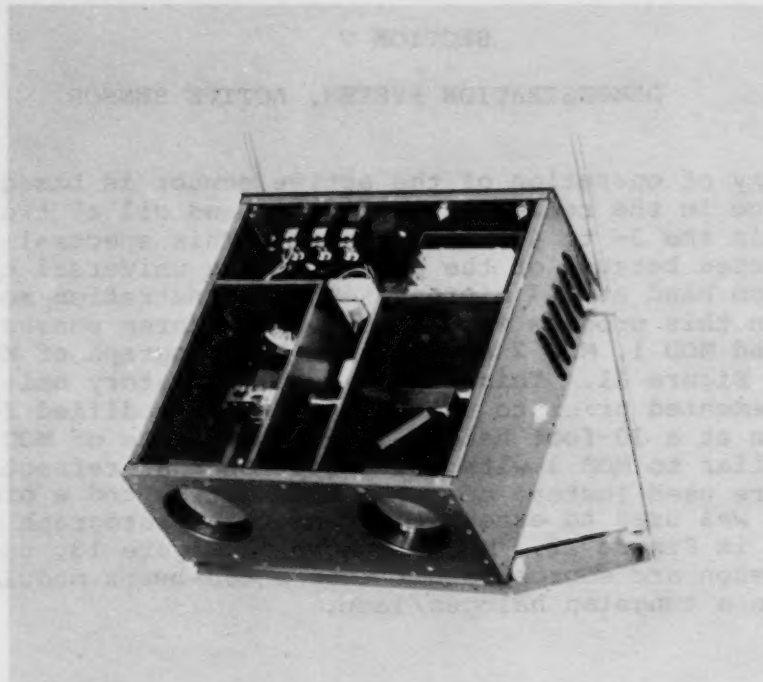


Figure 12. Active Sensor, MOD 2



Figure 13. Active Sensor, MOD 3

System Theory of Operation

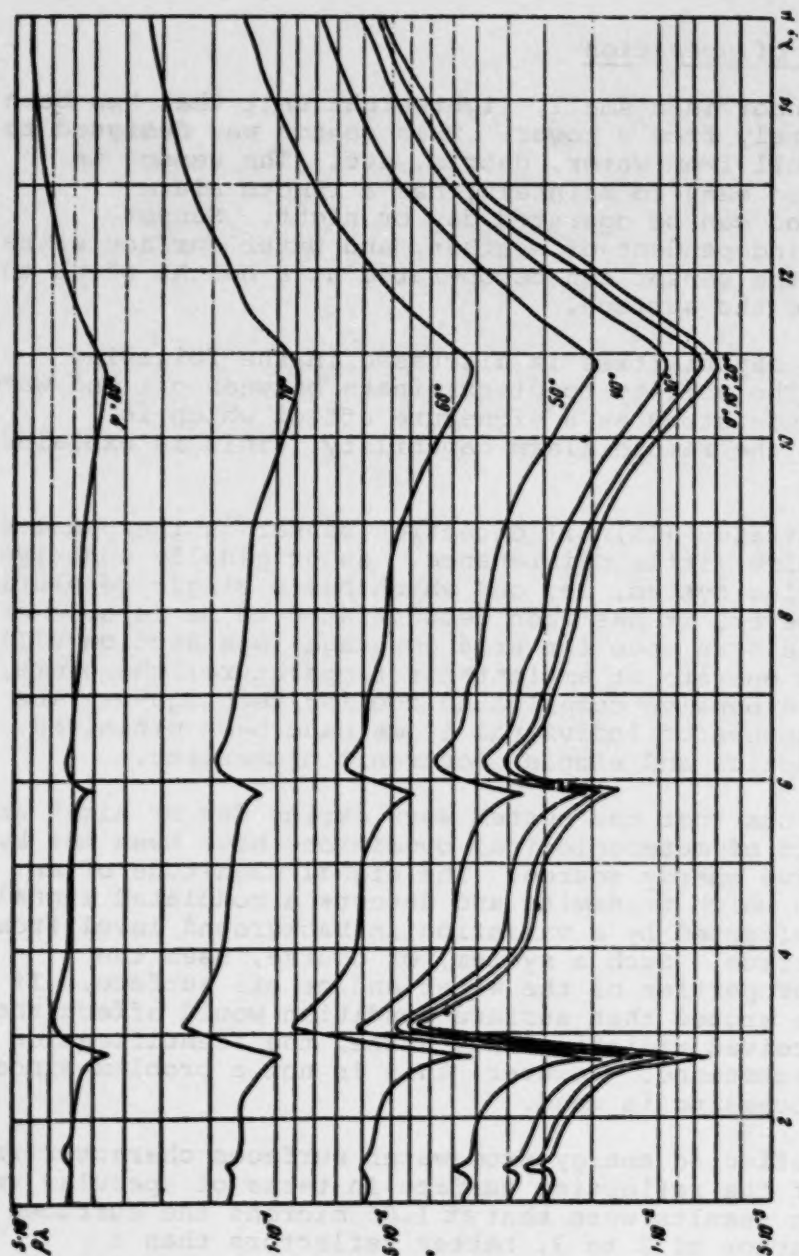
The active sensor is a small, lightweight unit that has been operated remotely from a tower. This sensor was designed to discriminate oil from water, debris, etc. The sensor is inexpensive and easy to maintain, has a remote alarm capability, and can be operated day or night. Sensor operation is independent of weather, and water surface state. In addition, the sensor can be operated at a height of up to 300 feet above the surface.

Each of these capabilities is discussed in the following paragraphs. The ability to discriminate between oil and water can best be understood as a signature effect which is equivalent to the remote alarm capability. This is explained in detail.

The active infrared (IR) oil detection sensor is inexpensive and will require little maintenance. As originally conceived it was a staring system, ie, one which has a single resolution element. However, it has been demonstrated to be capable of operating in a scan mode for area coverage (see Section VII). The detectors operate at ambient air temperature; therefore, requiring no expensive complicated cooling techniques. The number and expense of individual items have been minimized, using small optics and simple electronic processing.

The requirements that the system work during day or night and be independent of meteorological conditions have been met by using an active energy source. The signal magnitude of an active system which transmits and detects a modulated signal will not be affected by a variation in background level from the water surface. Such a system, of course, uses the reflectance properties of the water and/or oil surface. It might then be argued that surface condition would affect the amount of received radiation and, hence, the identification of the surface substance. However, this is not a problem since two-color processing is used.

A study¹ of reflected energy from water surfaces characterized the nature of the reflecting surface in terms of specular versus diffuse. The results were that at 1.06 microns the surfaces were, by a factor of 2 to 3, better reflectors than a Lambertian surface of the same reflectivity at the specular surface. This should be coupled with the measured results from a specular surface available in the literature. The reflectance of a water surface is shown in Figure 14. The data are of reflectivity versus wavelength as a function of aspect angle for a bistatic measurement. As can be seen,



• INFRARED
RADIATION;
MIKAEL A.
BRANSON
PLENUM PRESS,
1968
PP 553-594.

123014

Figure 14. Spectral Reflectance of Water in the Infrared Region for Natural Polarization and Selected Angles of View*

the absolute reflectance at a fixed wavelength varies strongly with aspect angle, while the ratio of reflectivity coefficients is essentially independent of aspect. If the diffuse reflectance is thought of as a series of specular reflectance events, then the ratio of reflected return at two different wavelengths should be essentially independent of surface condition. This would be true even though the absolute return of each of the single wavelength channels would vary by several orders of magnitude for a variance in surface conditions. Hence, if it desired to measure the specular reflectivity of a liquid surface with wave action the reflectance at two wavelengths should be measured and then ratioed. The result will be the ratio of the specular reflectivity at wavelengths.

To actually implement the effect of ratioing, the real-time log processors, developed for a multicolor radiometer and further refined on this program, were used. Prior to discussing the actual active system and the detailed block diagram of the analog processing circuitry, the final question of remote-alarm capability should be resolved. To have a remote alarm, strong signatures of oil and water should be found. Oil signature means the ratio of reflected radiance at two different wavelengths. The voltages used in forming the signature are obtained by processing the output of two detectors, one filtered for λ_1 and the other for λ_2 . This can be expressed as:

$$V(\lambda_i) = R_i r(\lambda_i) S P_t(\lambda_i)$$

where

$V(\lambda_i)$ = the voltage from the detector filtered at λ_i

R_i = system response at λ_i

$r(\lambda_i)$ = surface reflectivity (normal specular) at λ_i

S = scattering factor due to surface condition and aspect

$P_t(\lambda_i)$ = total power from the transmitter at the surfaces which is in the detector's field-of-view

The signature between λ_1 and λ_2 is, therefore

$$\phi_{12} = \ln V(\lambda_1)/V_{B1} - \ln V(\lambda_2)/V_{B2}$$

where V_{B1} and V_{B2} are fixed bias voltages in the log processors.

$$\phi_{12} = \ln [r(\lambda_1)/r(\lambda_2)] + \ln [R_1 P_t(\lambda_1)/R_2 P_t(\lambda_2)] \\ - \ln[V_{B1}/V_{B2}]$$

Note that S has dropped out of the signature since it was the same for both wavelengths. By setting the bias voltages properly in the log processor

$$\phi_{12} = \ln [r(\lambda_1)/r(\lambda_2)].$$

For reliable remote-alarm capabilities, the signature for water should be significantly different from that of oil; therefore, two wavelengths are needed which offer highly contrasting signatures. All wavelengths shorter than 1.5 microns have not been considered here because of water subsurface effects.

Oil which is polluting water remains on the surface of the water. This is unlike other forms of chemical water pollution where the pollutant is the bulk of the water itself. The former case is fortunate since this means that conceivable the areal extent and total amount of the oil can be remotely determined. However, precautions should be taken to avoid interference with subsurface conditions. Figure 15 gives the absorption coefficient and normal reflectance respectively for pure water, from 1 to 5 microns². Water appears transparent in the visible, and, as can be seen from the absorption coefficient, this continues until 1.5 microns is reached. From this point on the water becomes strongly absorbing. For example, the skin depth for water at 3.4 microns is only 12.0 microns. This strong absorption continues out into the 8- to 14-micron region.

The conclusion is that to avoid any subsurface effects in the water, a system should operate at wavelengths beyond 1.5 microns.

Figure 15 shows that a strong log ratio signature for water can be achieved by using one wavelength in the region of 3.0 to 3.5 microns and the other in the vicinity of 4.0 microns. The strong variation in the shape of the reflectance curve is characteristic of a resonance absorption. In this case it is the hydroxyl (O-H) vibrational mode. The resonance absorption affects the dielectric constant of the material, and hence, the index of refraction. The shape of this curve is well known and is an anomalous dispersion curve³. It has the dependence that the reflectance is minimum for the wavelengths shorter than the absorption and maximum for wavelengths that are longer.

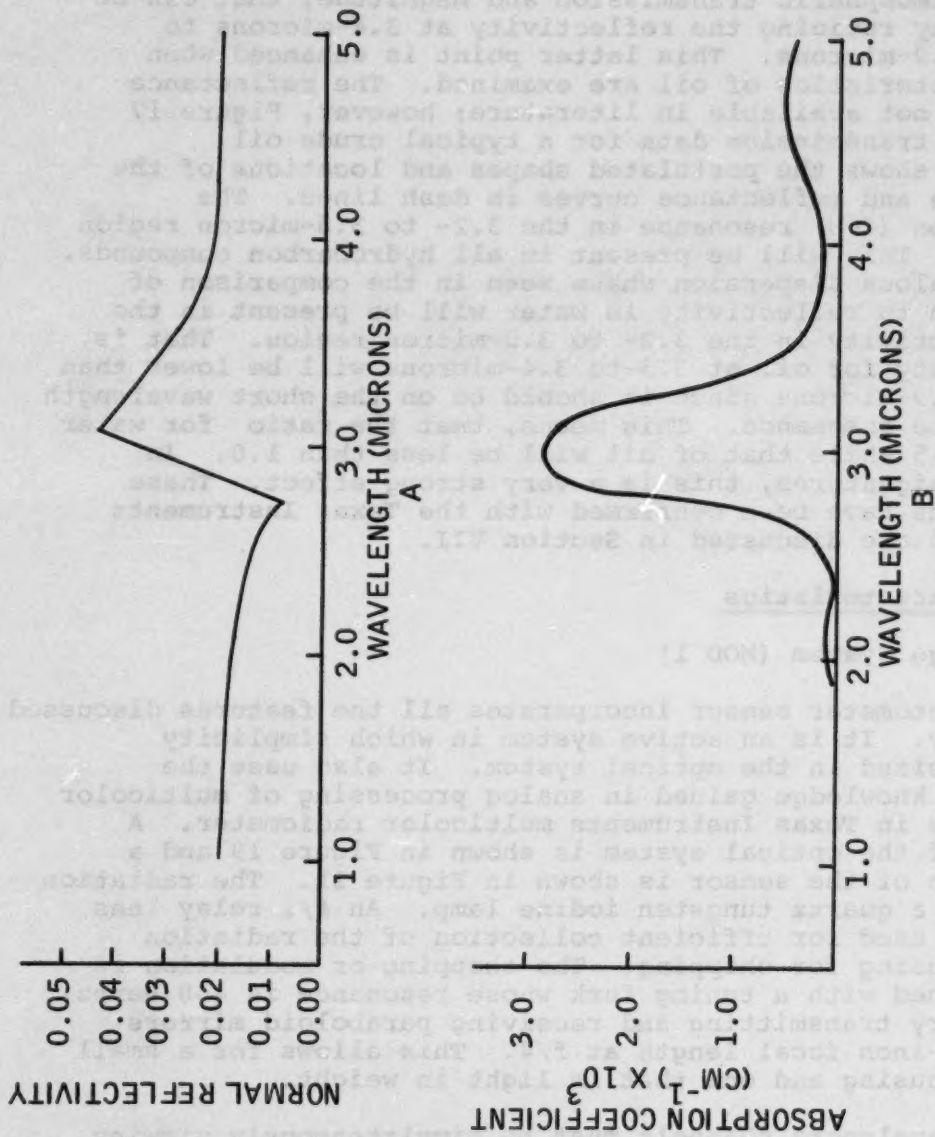


Figure 15. Absorption Coefficient and Normal Reflectivity of Pure Water

The wavelengths for maximum signature from water would be 2.75- and 3.1-microns. The short wavelength sample must, however, be taken at a wavelength longer than 3.3 microns because of the water vapor atmospheric attenuation in the 2.4- to 3.3-micron region. Figure 16 shows the transmission of a 1000-foot strong water signature, practical in terms of both atmospheric transmission and magnitude, that can be obtained by ratioing the reflectivity at 3.4-microns to that at 3.9-microns. This latter point is enhanced when the characteristics of oil are examined. The reflectance data were not available in literature; however, Figure 17 gives the transmission data for a typical crude oil. Figure 18 shows the postulated shapes and locations of the absorption and reflectance curves in dash lines. The hydrocarbon (C-H) resonance in the 3.2- to 3.5-micron region is noted. This will be present in all hydrocarbon compounds. This anomalous dispersion shape seen in the comparison of absorption to reflectivity in water will be present in the oil reflectivity in the 3.2- to 3.5-micron region. That is, reflectivity for oil at 3.3- to 3.4-microns will be lower than that at 3.9-microns since it should be on the short wavelength side of the resonance. This means, that the ratio for water will be 1.5 while that of oil will be less than 1.0. In terms of signatures, this is a very strong effect. These conclusions have been confirmed with the Texas Instruments sensor and are discussed in Section VII.

System Characteristics

Short Range System (MOD 1)

The reflectometer sensor incorporates all the features discussed previously. It is an active system in which simplicity was emphasized in the optical system. It also uses the circuitry knowledge gained in analog processing of multicolor signatures in Texas Instruments multicolor radiometer. A drawing of the optical system is shown in Figure 19 and a photograph of the sensor is shown in Figure 11. The radiation source is a quartz tungsten iodine lamp. An f/1 relay lens system is used for efficient collection of the radiation and refocusing for chopping. The chopping or modulation is accomplished with a tuning fork whose resonance is 400 Hertz. The primary transmitting and receiving paraboloid mirrors have a 10-inch focal length at f/4. This allows for a small optical housing and one that is light in weight.

The two wavelength channels must be simultaneously viewing the surface area, illuminated by the transmitting portion of the system. This is achieved by using one of the two narrowband interference filters as a beamsplitter.

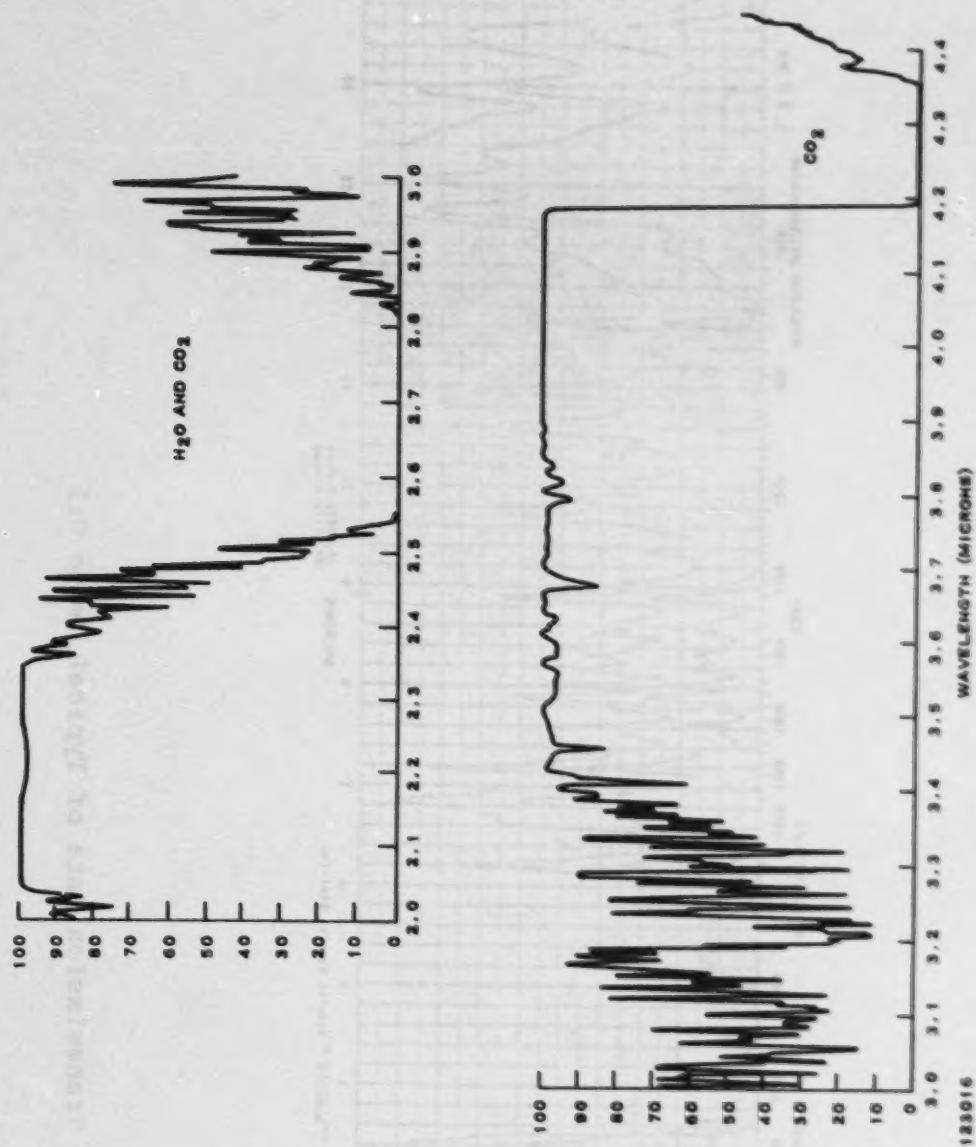


Figure 16. Transmission of a 1000-Foot Horizontal Air Path at Sea Level, 5.7 mm Precipitable Water and 79°F Temperature

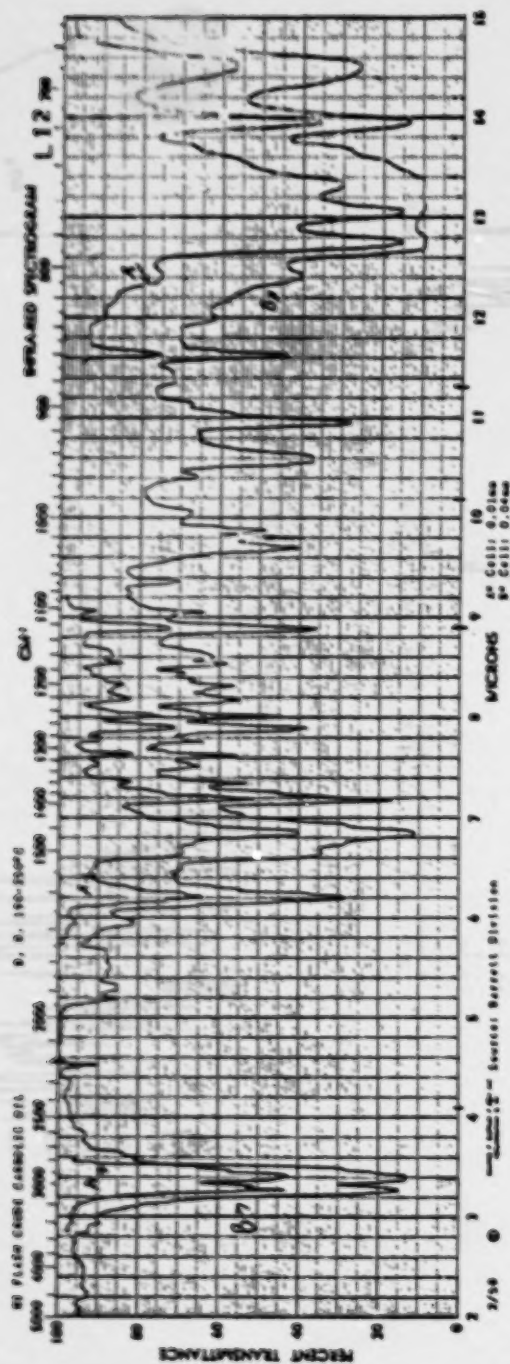


Figure 17. Transmission Data of Typical Crude Oil

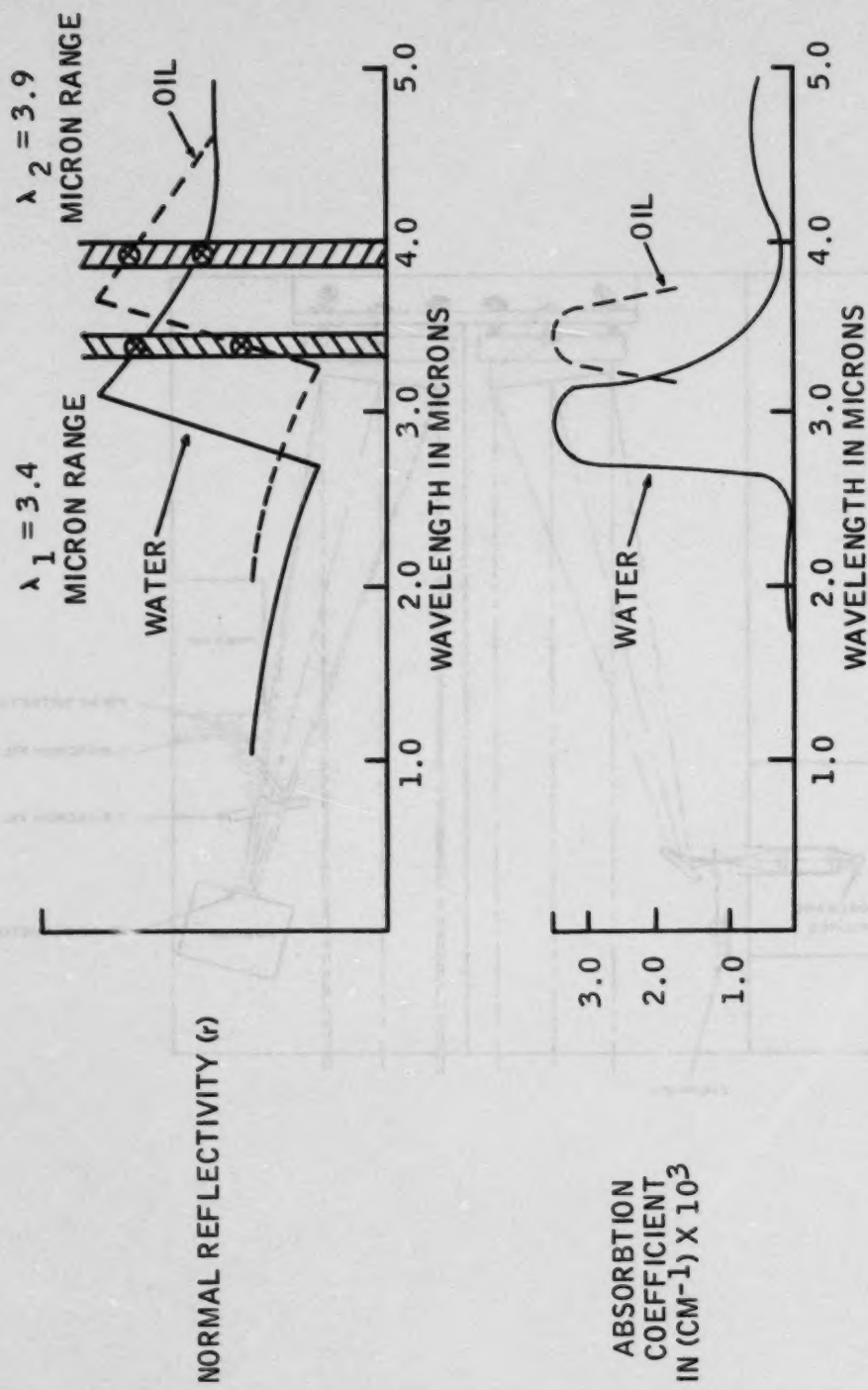


Figure 18. Postulated Shape and Location of Normal Reflectance and Absorption Coefficients of Oil Relative to Those of Water

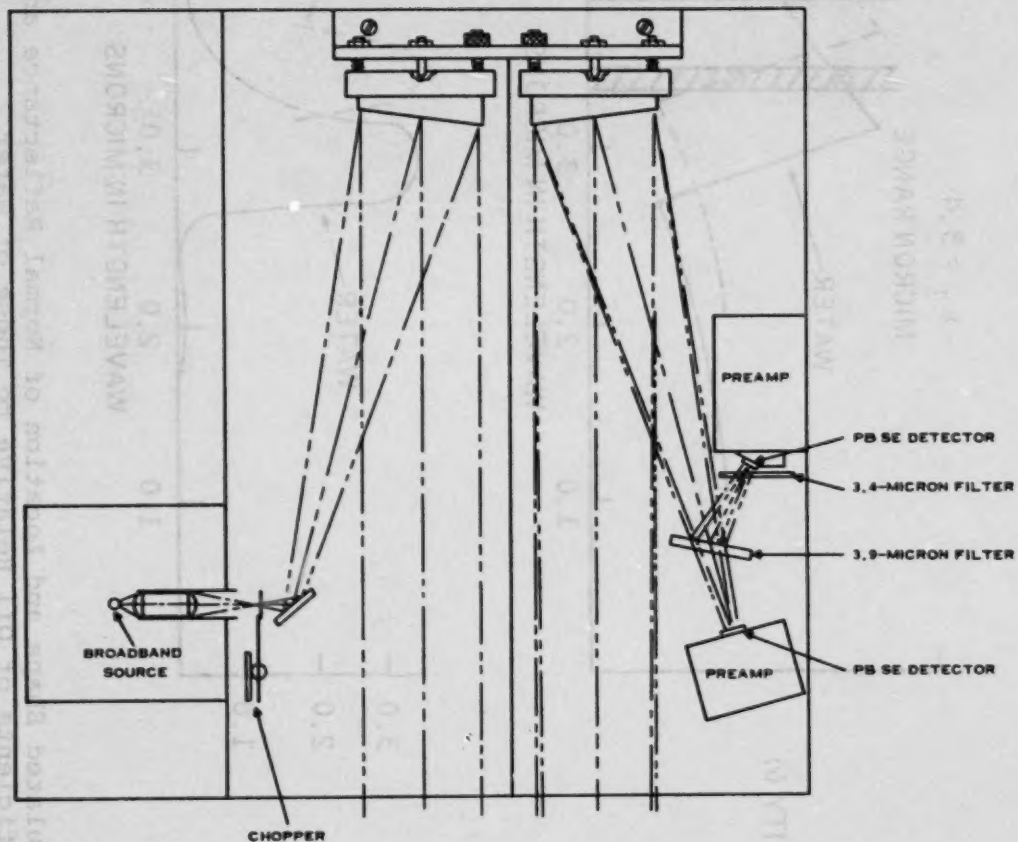


Figure 19. Optical Schematic of Active Infrared Oil Detection System, MOD 1

This interference filter passes only radiation in a 0.15 micron bandwidth centered at 3.9 microns. All other radiation is reflected from that filter. The portion of the reflected radiation in a similar band at 3.4 microns is then passed by the second filter. Lead selenium (PbSe) detectors are then placed behind each filter. These detectors operate well at earth ambient temperatures.

A block diagram of the electronics is shown in Figure 20. The preamps use a field effect transistor (FET) input stage and are mounted directly on the detector housings. All other electronic stages have integrated circuit (IC) operational amplifiers. A dual transistor located in each log amplifier circuit provides an output slope that depends on the temperature of the junction of these transistors. Hence, to improve the balance between the two analog channels, the two dual transistors have a common temperature reservoir.

The characteristics of the processing circuitry are given in Table 1. Although the system had been used for only specular surfaces in the laboratory prior to this contract, minor changes were made to permit operation off of nonspecular surfaces at a range of 30 feet and in a field environment. These changes included: the design of power supplies for the analog electronics, chopper driver and TE coolers in the detector, improvements on the housing and optical mounts, the selection of a better light source, the reduction of microphonic noises, and improved matching of log amplifiers and RC (resistive-capacitive) time constants.

The original system used a quartz-iodine tungsten filament lamp as a source. The quartz envelope provides suitable transmission in the 3- to 4-micron region while the tungsten has an effective blackbody color temperature of 3000°K. One of the problems with the lamps was the inefficiency of the geometry. The filament size was a 3/8- by 1/8-inch coil. Radiation from only a small portion of the total filament was being captured by the relay lens system and collimated by the transmitting mirror. A special purpose lamp was located with a small active element. By using this lamp and a larger aperture chopper at the same frequency, the relay lens system was eliminated with an increase in the total optical through-put. Note that the constraints on the system are that the area illuminated and the area viewed are approximately the same. The focal lengths and diameters of the transmitting and receiving mirrors were kept the same for simplicity of alignment. This MOD 1 was used in the first step in the evaluation of the system and the technique in a field test at a range of 30 feet.

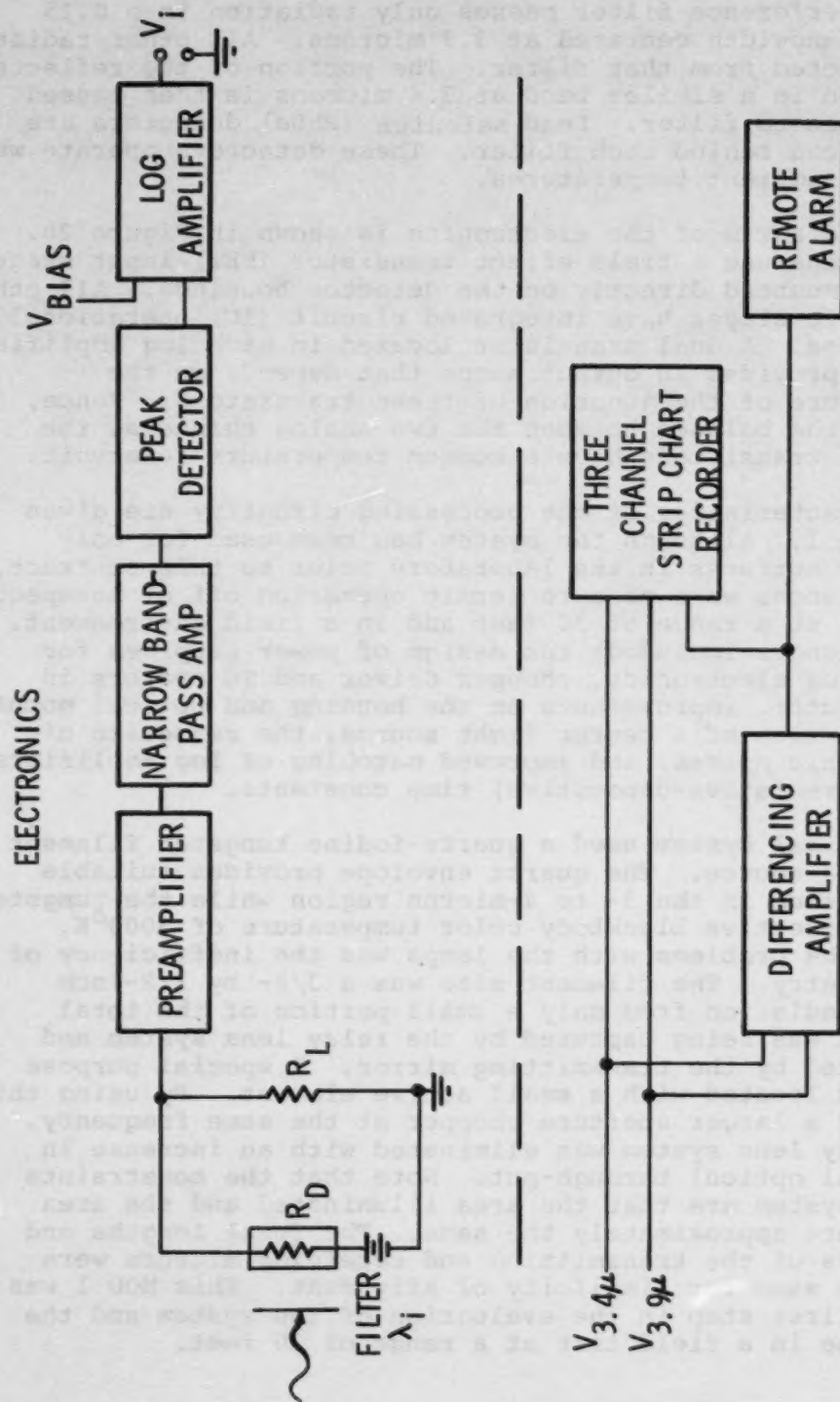


Figure 20. Block Diagram of Processing Circuitry

TABLE 1. CHARACTERISTICS OF CIRCUIT ELEMENTS

	3.4 Microns Channel	3.9 Microns Channel
Narrow Bandpass Amplifier		
(a) Gain at 400 Hz	52 dB	70 dB
(b) Q	9.3	16
DC + NBP Amplifier		
(a) DC Level for for 1-mV rms input	0.47V	3.7V
(b) Noise for 1-K Load	1mV	3mV
Log Amplifier		
(a) 0.1-V input	-2.30	-2.30
(b) 1.0V input	0.00	0.00
(c) 2.0V input	+0.69	+0.69
Preamplifier		
(a) Gain	20 dB	20 dB
(b) Input noise for 400-K source resistance	0.02 V/Hz	0.02 V/Hz

Long Range System (MODS 2 and 3)

The main emphasis on extending the range of the system was placed on improvement of signal-to-noise ratio by optimizing the optical design in both the transmitter and receiver. An important part of this design consisted in determining the best field of view (FOV) for the environment where the equipment would be installed. This was done by performing a detailed study of the wave action on seas and large lakes.

A certain fraction of a natural wave will always present a facet which will be normal to the view angle. This is demonstrated in Figure 21. This Figure gives the probability that the sea surface slope, B , is less than or equal to β . This is plotted as a function of β . Figure 22 gives the same data but plotted as the slope probability density versus β . On the basis of this data set it is seen that the maximum return would be obtained from a beam striking the surface at 14° from the normal. This angle depends on the state of the water surface. Examples of this effect are given in the test sections.

Since a fraction of the wave surface always gives a normal reflection back, the most direct approach to the problems of an active system is to have the area illuminated greater or equal to the largest wave period. Also the area viewed should be equal to the area illuminated for optimum efficiency. If the distance from peak to peak of the largest waves to be encountered is X_0 , then the FOV of the transmitter and receiver should be $X_0/2$. A design goal for the spot size was on the order of 2.5 to 4 feet for 100 foot altitude which is 7 to 12 feet at 300 feet. This corresponds to FOV's of 24 to 40 milliradians. The large FOV values imply that short focal length systems be used for both the transmitter and receiver. Also, the aperture must be wide to give strong capture power.

Design criterions for the optical system were:

1. Wide aperture compatible with filament area of light source, the desired illuminated area, and the area of available detectors.
2. FOV greater than or equal to the wave period.
3. FOV of transmitter and receiver equal.
4. Simple, inexpensive, and easy to maintain.
5. Easy to align in lab or in the field.

6. Capable of being prealigned in the lab.

7. Easily reset when instrument is relocated at a different height.

Transmitter Optics

The tungsten-iodine lamp was the source originally used for this systems application. The reason is that it is simple to incorporate and at the same time has many good spectral characteristics. The maximum color temperature is on the order of 2900°K which gives spectral efficiencies on the order of 5×10^{-2} for the 4-micron region.

While this is not as good as a globar it is power that can be used efficiently in a lens system due to the small filament size. The one problem is that it is a continuous source that must be mechanically modulated. This dictates that the f-number for a system using a tungsten lamp be on the order of 1.5 which thereby reduces the collection capability of an optimized collecting optical system. The color temperature is discussed in more detail later in this section in terms of lamp lifetime.

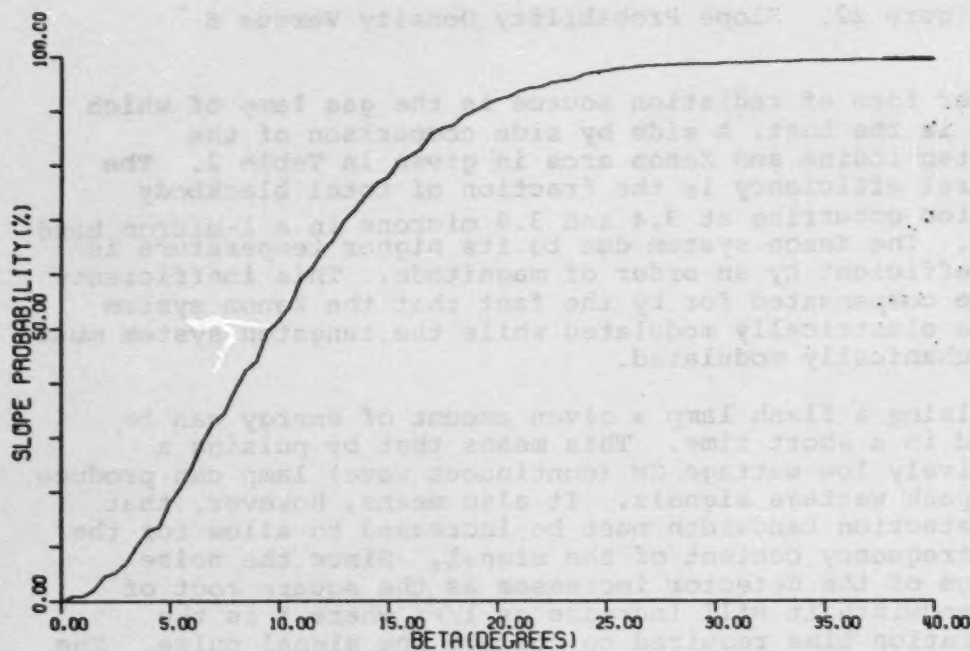


Figure 21. Probability that Sea Surface Slope is Less than or Equal to β Versus β

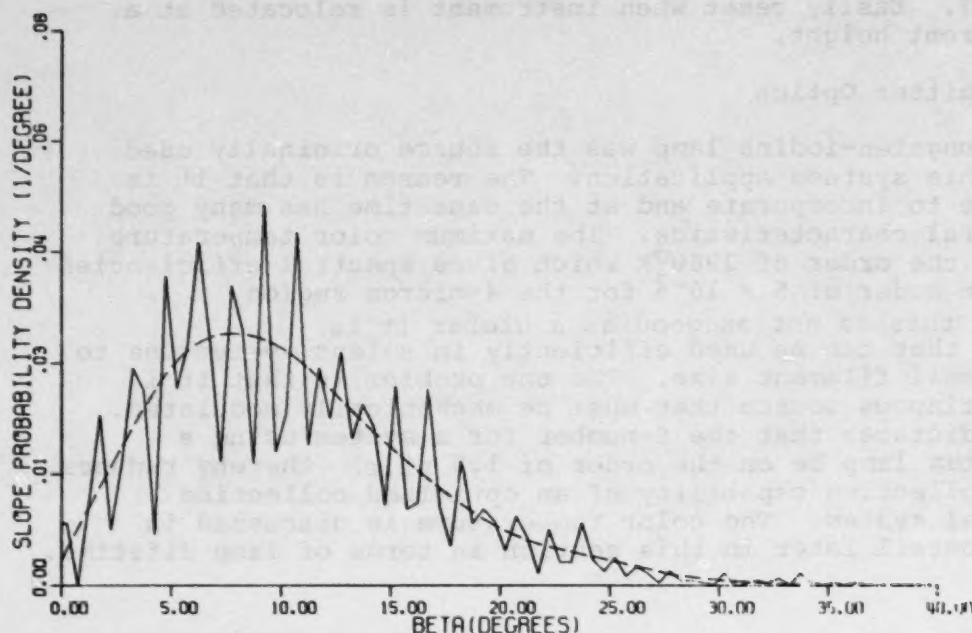


Figure 22. Slope Probability Density Versus β

Another form of radiation source is the gas lamp of which Xenon is the best. A side by side comparison of the tungsten iodine and Xenon arcs is given in Table 2. The spectral efficiency is the fraction of total blackbody emission occurring at 3.4 and 3.9 microns in a 1-micron bandwidth. The Xenon system due to its higher temperature is less efficient by an order of magnitude. This inefficiency can be compensated for by the fact that the Xenon system can be electrically modulated while the tungsten system must be mechanically modulated.

By pulsing a flash lamp a given amount of energy can be dumped in a short time. This means that by pulsing a relatively low wattage CW (continuous wave) lamp can produce high peak wattage signals. It also means, however, that the detection bandwidth must be increased to allow for the high frequency content of the signal. Since the noise voltage of the detector increases as the square root of the bandwidth it will increase as $1/\sqrt{\tau}$ where τ is the integration time required to collect the signal pulse. The peak signal increases as $1/\sqrt{\tau}$ since the energy is being dumped in that time period. The signal-to-noise ratio then goes as $1/\sqrt{\tau}$.

TABLE 2. TRANSMITTER

PARAMETER	TUNGSTEN (2900°K)	XENON (7000°K)
Spectral Efficiency $W(\lambda)$ total	$\lambda = 3.4\mu\text{m}: 6.20 \times 10^{-2}$	$\lambda = 3.4\mu\text{m}: 7.3 \times 10^{-3}$
(per micron)	$\lambda = 3.9\mu\text{m}: 4.0 \times 10^{-2}$	$\lambda = 3.9\mu\text{m}: 4.4 \times 10^{-3}$
Optical Efficiency		
Emissivity	0.1	0.1
Collection	≈ 0.003	0.75
$1/\sqrt{\tau}$	1.0	200.0
	($\tau = 1\mu\text{sec}$)	($\tau = 25\mu\text{sec}$)
Available Energy in 0.1 x 0.1 inches (joules)	44	100
Figure of Merit (per micron)	$\lambda = 3.4\mu\text{m}: 0.036$ $\lambda = 3.9\mu\text{m}: 0.023$	$\lambda = 3.4\mu\text{m}: 11.0$ $\lambda = 3.9\mu\text{m}: 6.6$
Comments	Possible loss of Optical Efficiency at high energy	

All of the lamp factors are combined to give a final figure of merit at the two wavelengths. As can be seen, even though the Xenon system is spectrally inefficient, it can produce a factor of 10 increase in system range over a system using tungsten-iodine lamp. There is one problem. Photon flux data has been taken with a Xenon lamp as a function of input energy for a low-powered lamp rated at 5 joules at 3.6 microns. The data was taken and as is shown in Figure 23 the signal does not increase linearly with input power. This is believed to be caused by either an increase in opacity due to an increase in current density or by the increase in black body temperature with an increase in energy input.^{5, 6}

The key reliability factor in the active system is the lamp lifetime. In order to obtain good collimation, lamps with small active areas have been used. These small, high wattage lamps usually have short lifetimes and hence become the limiting factor on time between system maintenance. The lifetime of a tungsten filament unit is inversely proportional to the thirteenth power of the applied voltage. The optimum lamp for the active system appears to be special tungsten halogen lamp made by Sylvania. The number is 60 Q/CL-8.5 volts. The data appears in Table 3.

TABLE 3. CHARACTERISTICS OF TUNGSTEN HALOGEN LAMP

Wattage	60
Design Voltage	8.5
Rated Lumens	1000
Life (hours)	50
Color Temp. ($^{\circ}$ K)	3100
Min. Bulb Wall Temp. ($^{\circ}$ C)	350
Max. Seal Temp. ($^{\circ}$ C)	450
Element (coil)	0.1 inch long by 0.1 inch diameter

Note that at 8.5 volts the rated life is 50 hours with a color temperature of 3100 $^{\circ}$ K. The latter value means that the $\lambda_{\text{peak}} = 0.94$ microns which determines the power distribution as a function of wavelength. The optimum operating level is a tradeoff of the power in the region of 3.4 and 3.7 microns and the life of the lamp. Figure 24 gives the lamp lifetime as a function of applied voltage, Figure 25 gives the power output at 3.5 microns as a function of applied voltage and Figure 26 shows the current versus applied voltage. Note

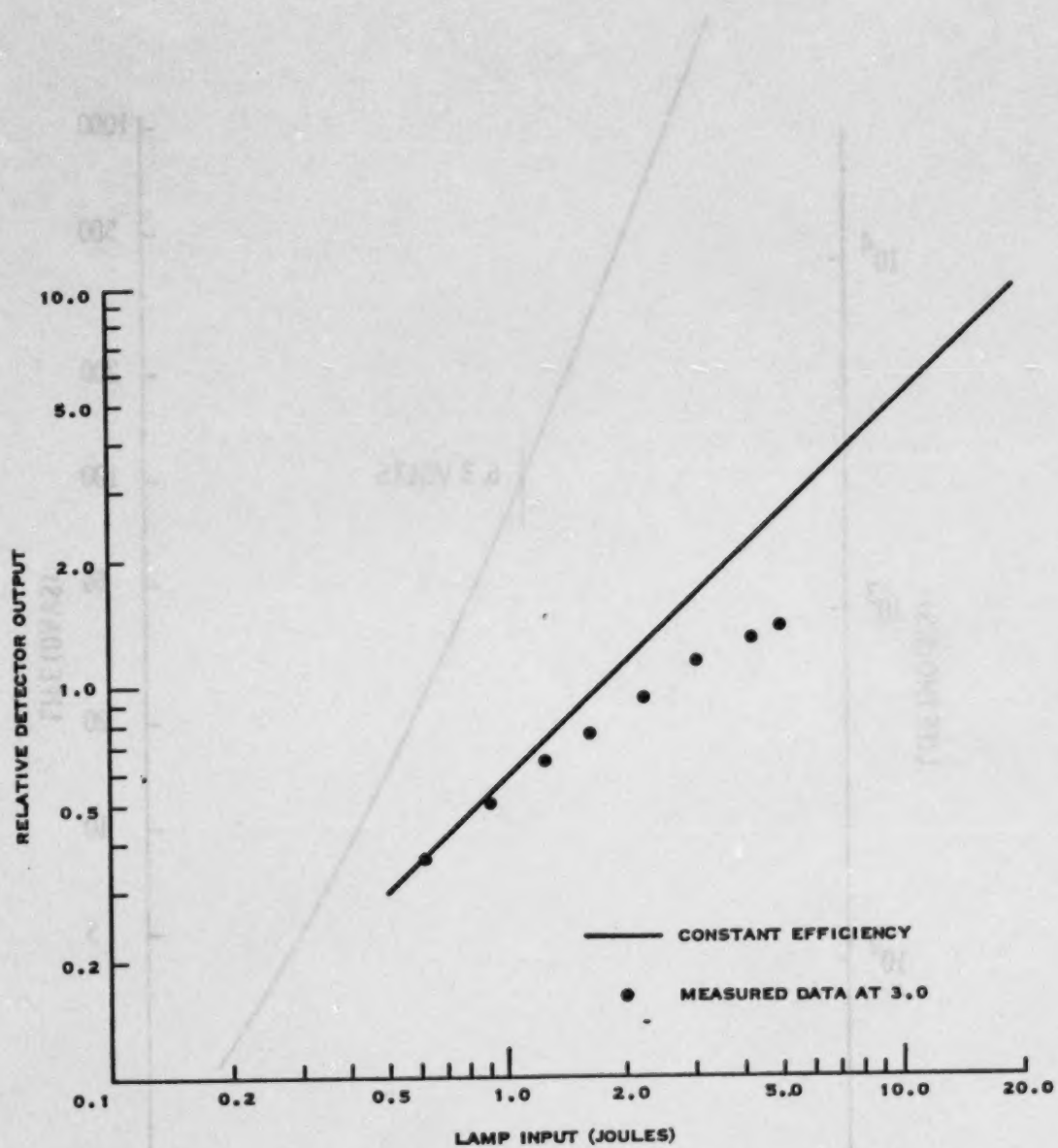


Figure 23. Relative Flux Output Versus Input Energy for Pulsed Xenon Lamp

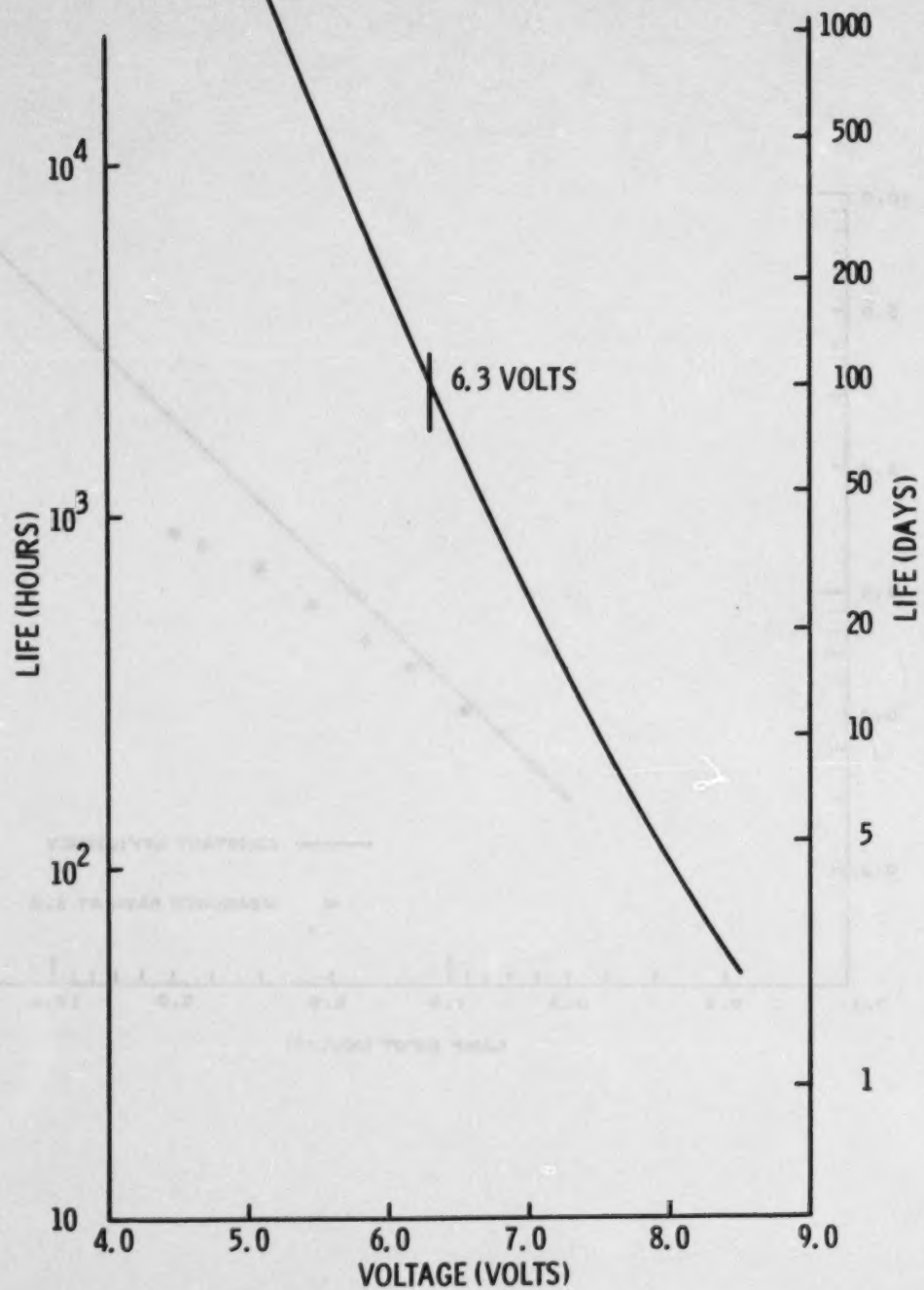


Figure 24. Lamp Life Versus Applied Voltage for a Tungsten Halogen Lamp

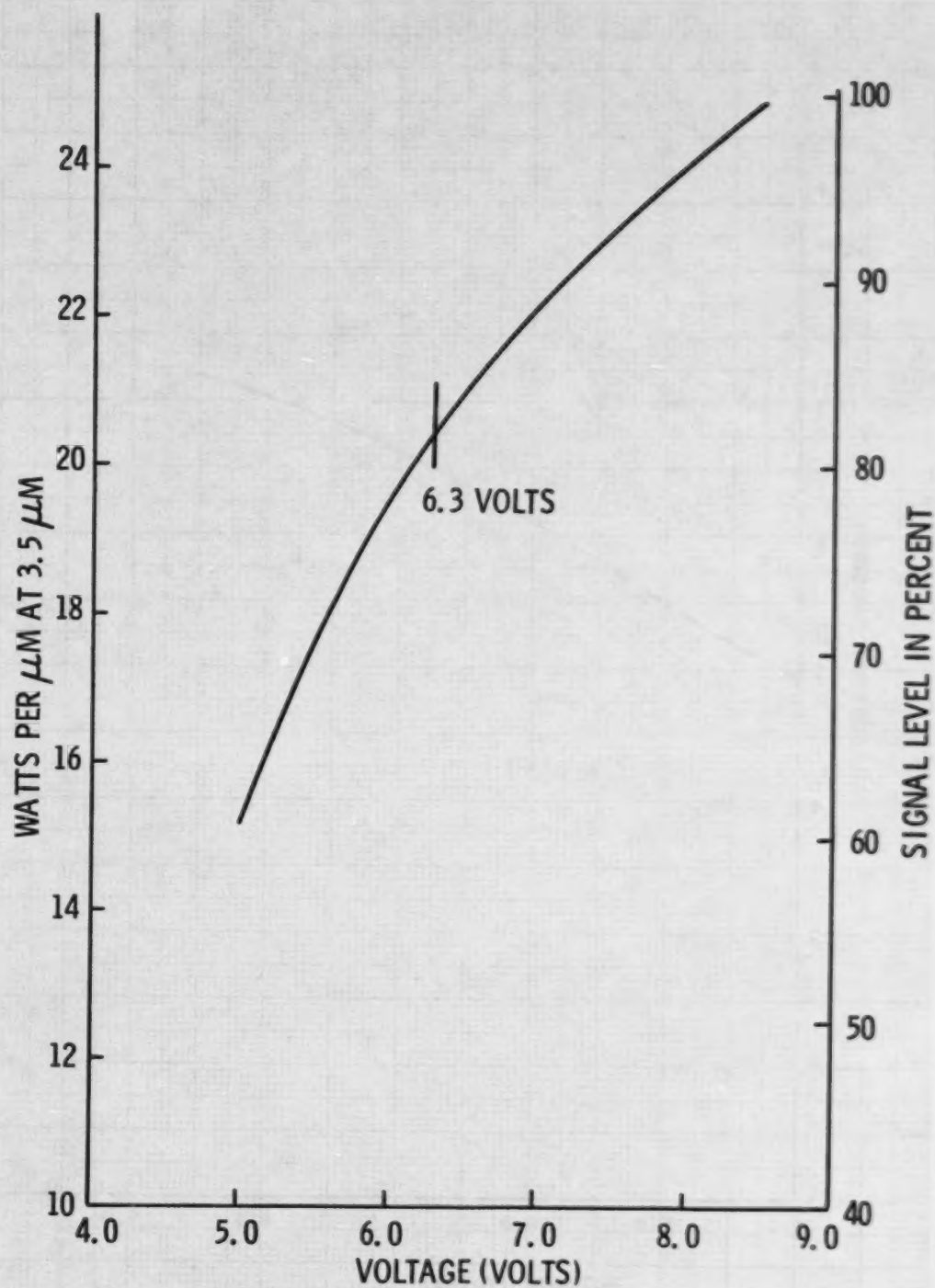


Figure 25. Emitted Power at 3.5 Microns as a Function of Lamp Voltage (Tungsten)

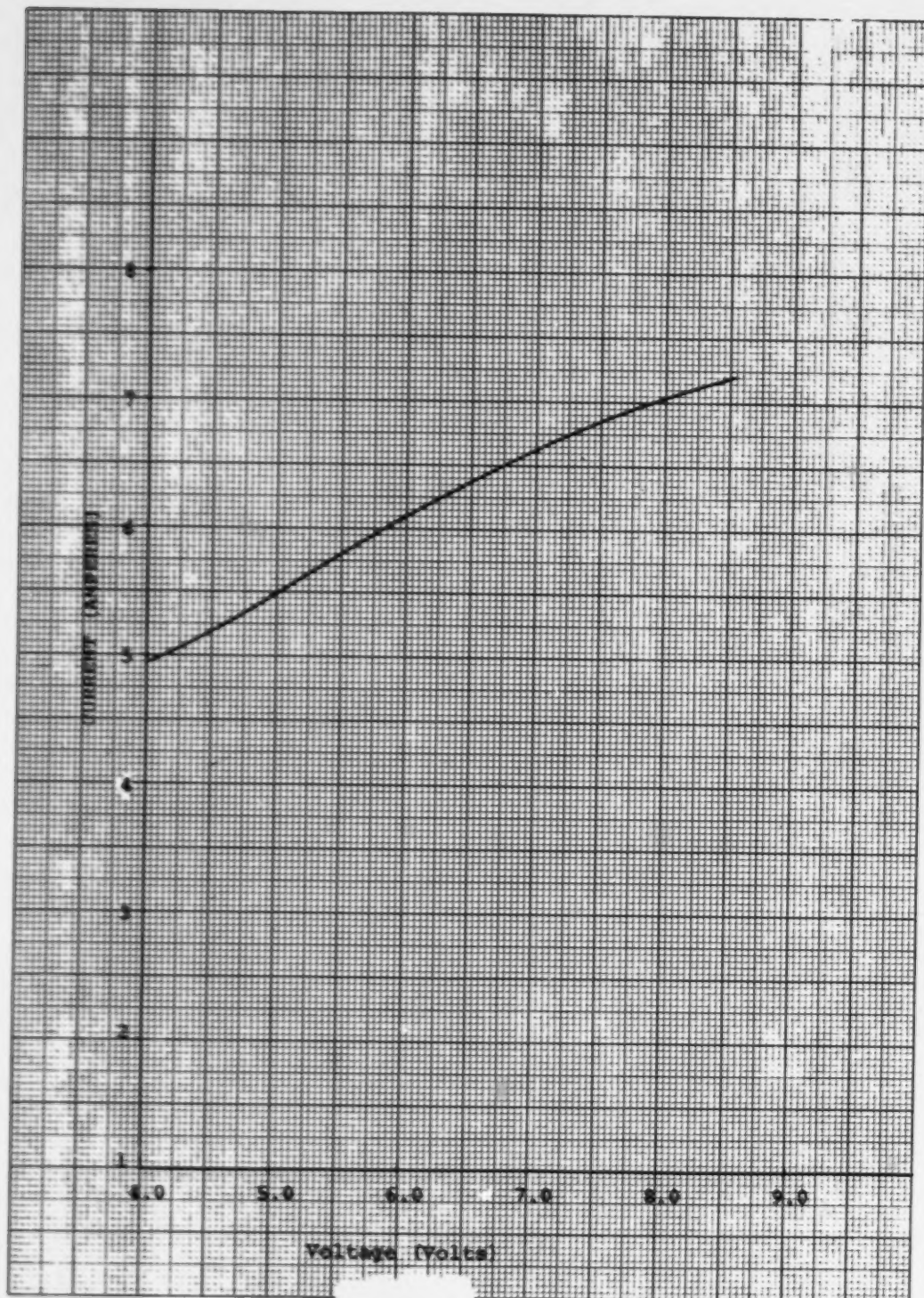


Figure 26. Current Versus Applied Voltage for a Tungsten Halogen Lamp

that by using 6.3 volts, a hundred days of operation can be obtained with a loss in signal of only 18%. Note that the lifetime can be increased to 200 days with a signal loss of 22%. That is, the lifetime has been doubled but the signal level has dropped only 4%. This, however, is not necessarily desirable. The 6.3 volts is an off-the-shelf transformer and, hence, the lamp supply is inexpensive. Also, 100 days is a reasonable maintenance time period for all electro optical equipment.

The lifetime of Xenon flash lamps is somewhat more complex than that of the tungsten lamp. The number of flashes not only depends on the energy per pulse but also the pulse duration. These are related by

$$N = \gamma^{-8.5}$$

where N = number of flashes

and $\gamma = E_o/E_x$ which is the ratio of lamp energy to explosion energy.

Again, small emitting areas are required. Two Xenon lamps, X-80 and X-160 made by Illumination Industries Inc, were selected. Their characteristics are given in Table 4. Note that instead of explosion energy, the single shot explosion energy constant is given. They are related by

$$E_x = C_e \tau^{1/2}$$

where C_e = single shot explosion energy constant and
 τ = pulse width

TABLE 4. CHARACTERISTICS OF XENON LAMPS

	X-80	X-160
Maximum Energy (joules)	25	100
Arc Spacing (mm)	1	1.5
Maximum Average Power, DC Operation (watts)	60	100
Maximum Average Power, Pulsed Conditions (watts)	75	150
C_e = single shot explosion energy constant (joules/sec ^{1/2})	1.19 x 10 ⁴	

Figure 27 shows N versus C_e for the X-80 lamp. It should be noted that 10^6 is a practical upper limit for N for any lamp, not just the X-80 lamp.

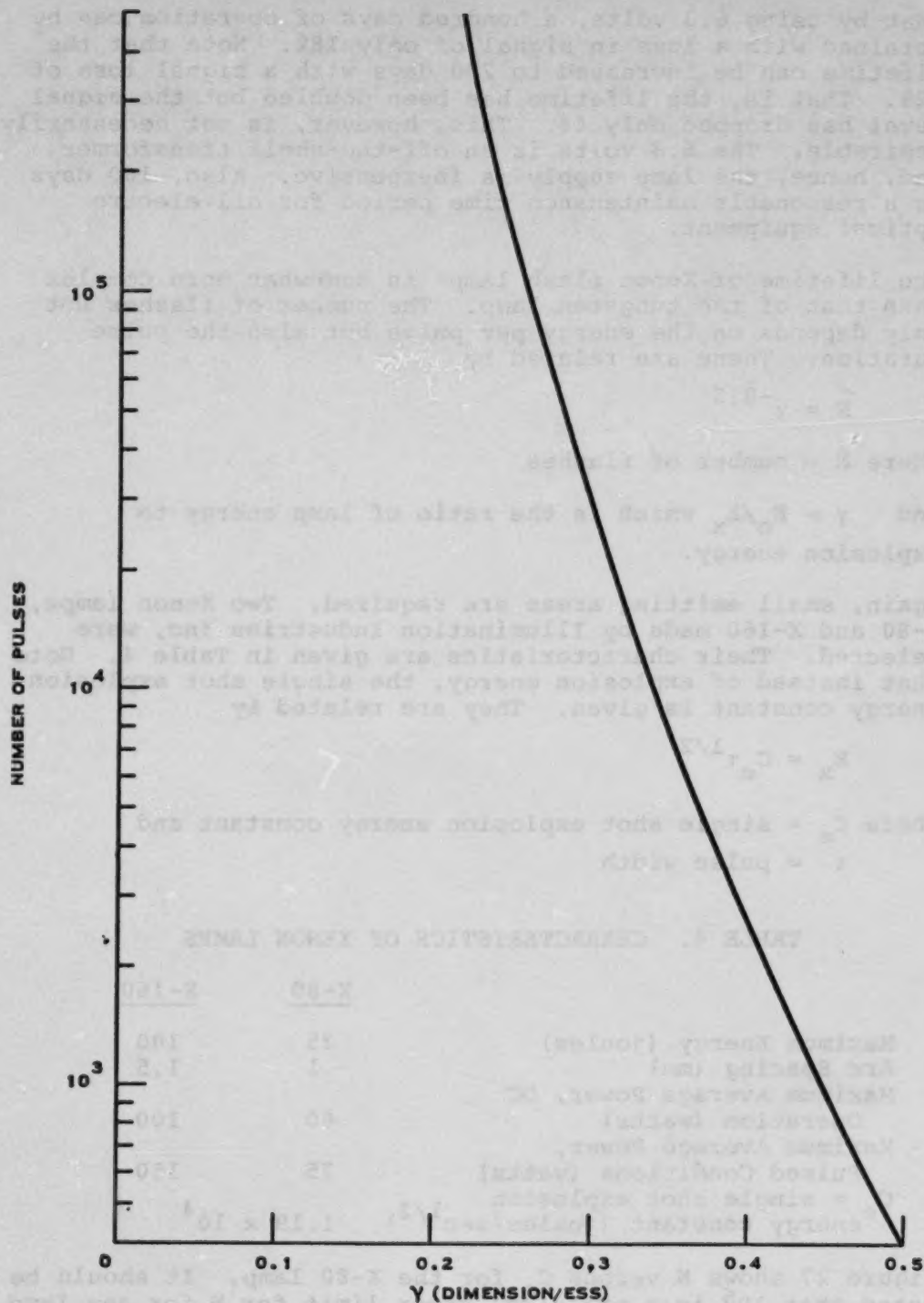


Figure 27. Number of Pulses Versus the Single Shot Explosion

Assuming a value of 10^6 for N the value of γ is 0.197.

Therefore

$$\begin{aligned}\tau^{1/2} &= E_0 / (0.197 C_e) \\ &= (4.22 \times 10^{-4}) E_0\end{aligned}$$

Figure 28 shows a plot of τ versus E . This is the limiting curve for the X-80 lamp in order to obtain 10^6 pulses. One important point is that the signal-to-noise ratio goes as $(E_0/\tau^{1/2})$. This is constant for a given lamp operating at the optimum energy point. It is, of course, not a constant if the lamp is not operated at optimum conditions. A plot of the relative signal-to-noise ratio as a function of the number of pulses given in Figure 29 for the X-80 lamp. Note that in order to gain a factor of two in the signal-to-noise ratio, the life of the lamp is decreased by almost three decades.

A study of existing lasers showed that the long-range system could not be fabricated cheaply with gas lasers and exceeded the efficiency of different type of source in a long term time period. Texas Instruments has a laser diode program for building tri-metal lasers which operate in the 4- to 12-micron region. The present materials used are PbSnTe and PbGeTe. In a pulsed mode, the lasers can produce up to 1 watt of power in a line width on the order of 10^{-5} cm. Also considered was the InSbAs diode. If this material develops, it can be tuned to the 3.4 micron region. Due to its very narrow line width, it will also be suitable for heterodyne detection. The application of this type of system is at least two years away.

In conclusion the following points are obvious. For a long life time system a tungsten-halogen lamp should be used and operated at a point below maximum rating. For example the 60 Q/CL-85 lamp operated at 6.3 volts. For applications of very long range a flash lamp should be used.

Receiver Optics

An improved receiver was designed for the long range system. An optical diagram of the unit is shown in Figure 30. It uses a 3.5-inch aperture refractive lens with an f-number of 1.4. The 3-mm square detectors used in the original unit were used. However, light pipes were added in front of the detectors to

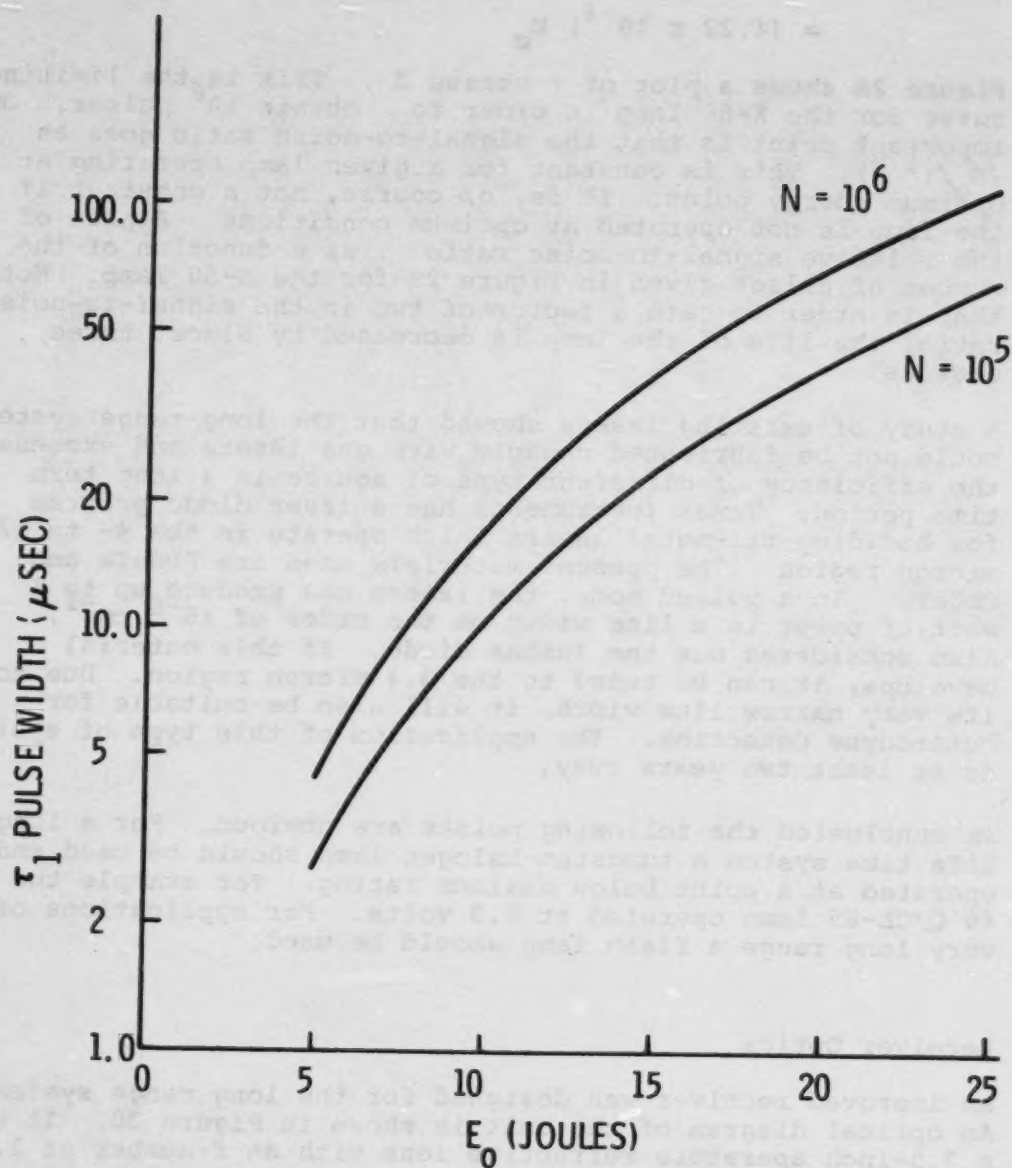


Figure 28. Pulse Width Versus Pulse Energy for X-80 Lamp

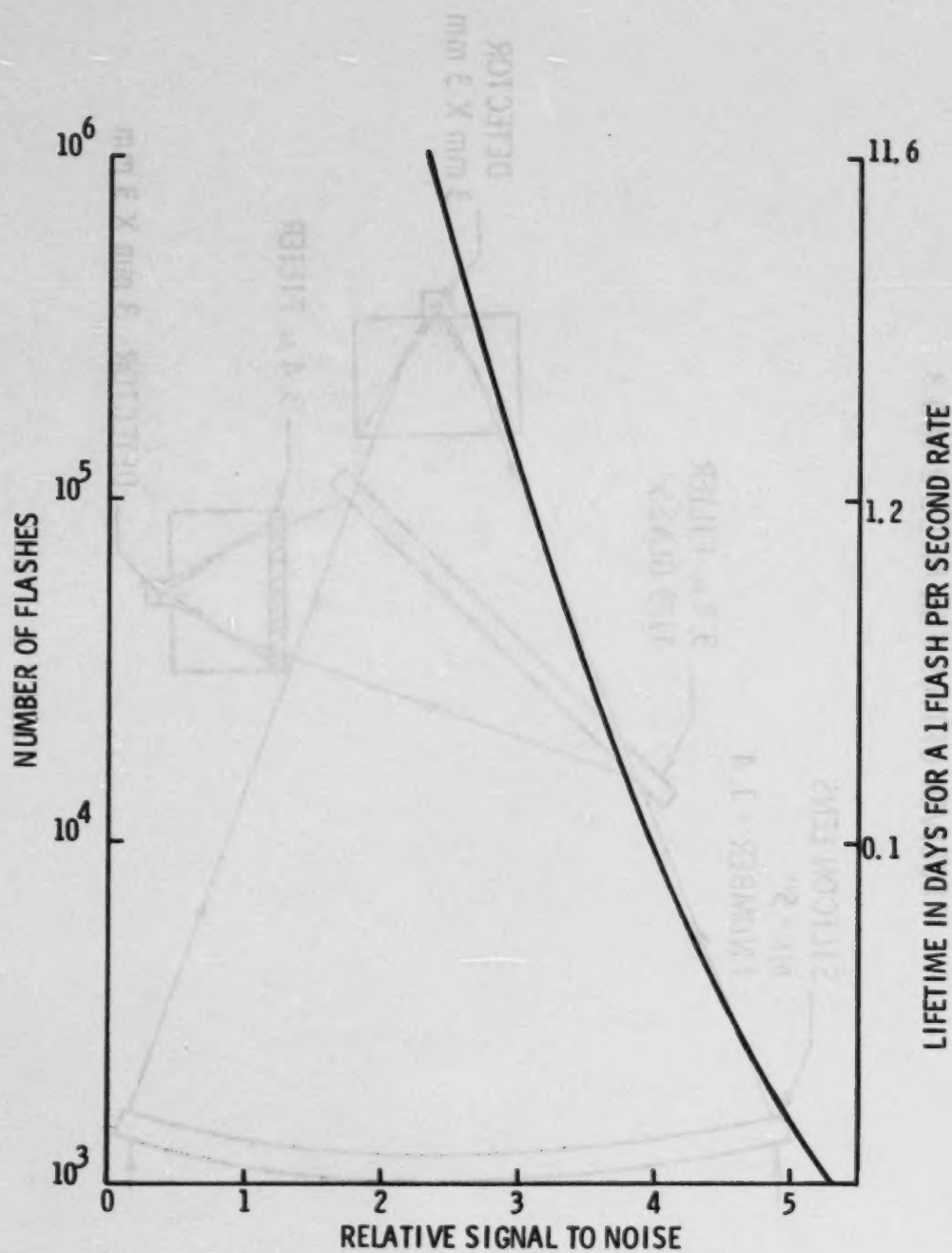


Figure 29. Number of Flashes of an X-80 Xenon Lamp Versus the Signal-to-Noise Ratio for a Pulsed Detection System

RECEIVER OPTICS FOR MODS 2 AND 3

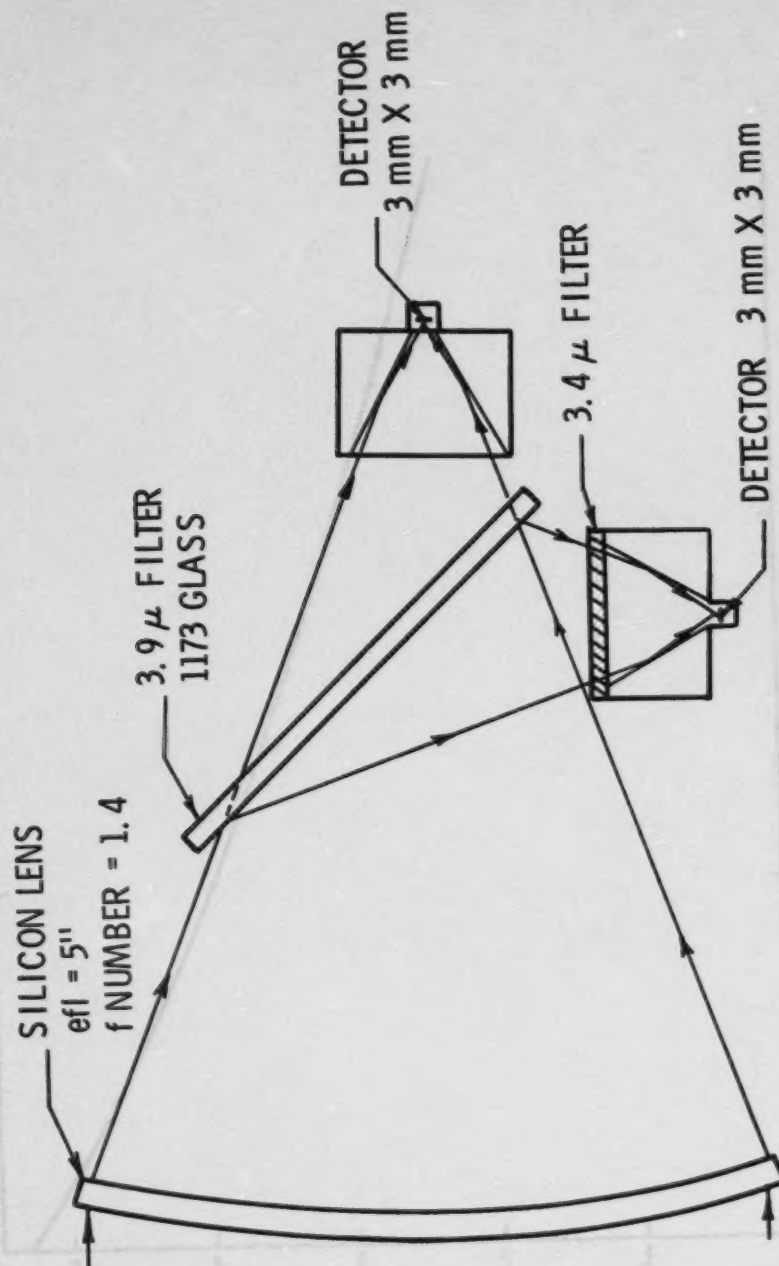


Figure 30. Receiver Optics

give an enlarged field of view (FOV) of 40 milliradians. This gives a versatility of 7.2- and 12-foot FOV's at 300 feet. In order to simplify the alignment procedure and to allow for a quick readjustment of the active sensor in the field when it is relocated at a different height, all of the receiver optics were mounted on an adjustable metal plate that was pre-aligned in the laboratory. By using a similar plate for the transmitter optics and micrometer head for angular control of each plate, the system can be preset per Figure 31 for any height between 30 and 300 feet.

In addition to the improvements made on the optical system discussed above, another area of possible significant improvement is in a change of detectors. At present the system uses PbSe with an inexpensive thermoelectric cooler. An alternative is to use InSb detectors mounted on open cycle Joule-Thomson coolers for 77°K operation. The advantages of this mode of operation are shown in Table 5. Note that the improvement in detectivity (units of $\text{cm}(\text{Hz})^{1/2} \text{ watts}^{-1}$) of the InSb detector is approximately a factor of 10 over the PbSe. However, still further improvement can be made since there is a cold reservoir available. This is shown in the cold stop factor and cold spectral filtering. These improvements result from aperturing the detector to remove some of the background and then removing all of the background except that which is in the desired spectral bandpass. The total increase in the figure of merit is approximately 10^2 or an increase in range of a factor of 10. This technique, while attractive, was not evaluated during this program due to the increase in the cost of mass produced systems.

TABLE 5. DETECTORS

	PbSe (240°K)	InSb (77°K)
D* (PEAK)	3.4 μm : $5 \times 10^9 \text{ W}^{-1} \text{ cm Hz}^{1/2}$	3.4 μm : $5.5 \times 10^{10} \text{ W}^{-1} \text{ cm Hz}^{1/2}$
(180°FOV)	3.9 μm : 6×10^9	3.9 μm : 7×10^{10}
Cold Stop Factor	-	2.0
Cold Spectral Filter	-	3.4 μm →8.9 3.9 μm →4.9
Figure of Merit	3.4 μm : 5×10^9 3.9 μm : 6×10^9	3.4 μm : 9.8×10^{11} 3.9 μm : 6.9×10^{11}

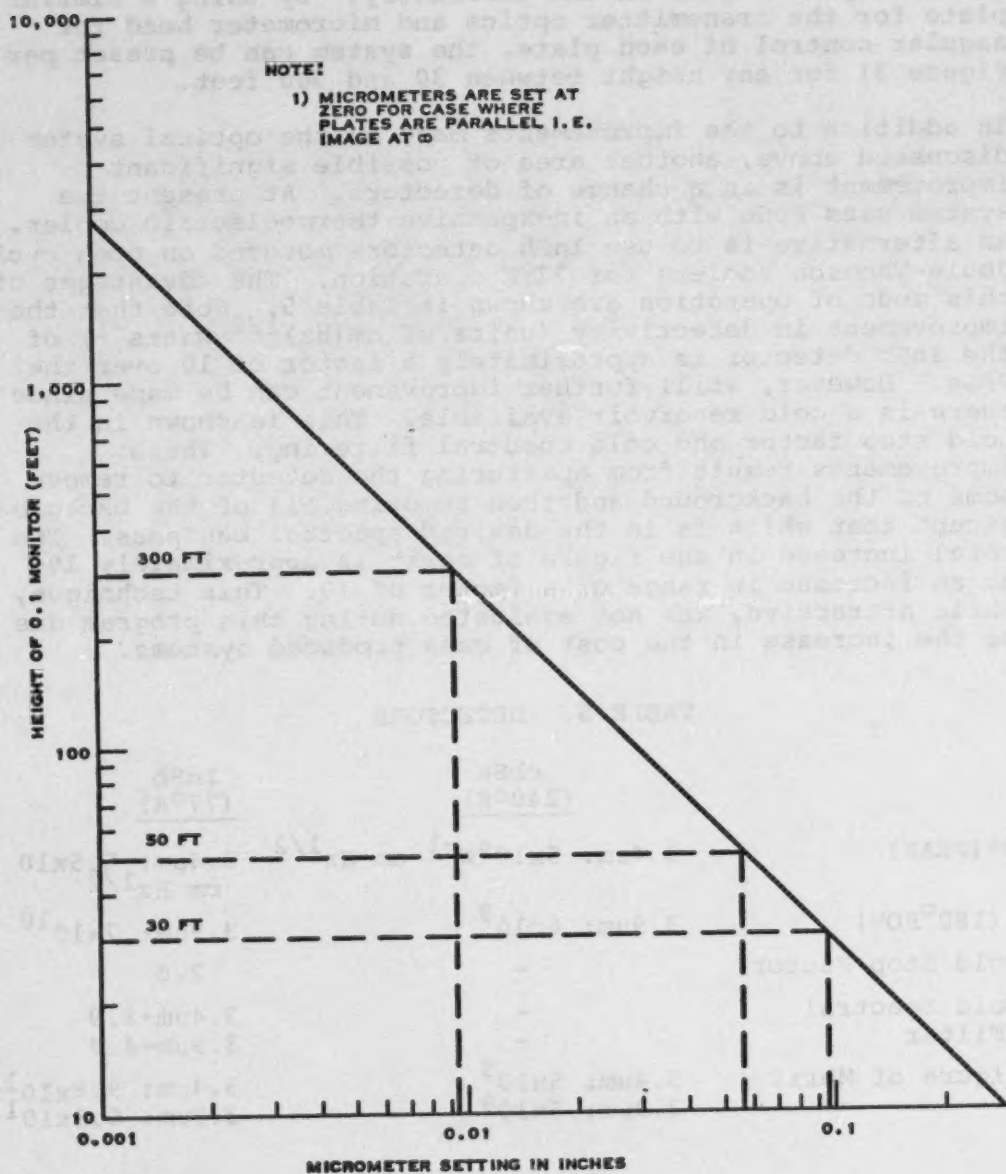


Figure 31. Optic Plate Adjustment Curve

Signature Optimization

As part of this program, a study was made of oil and water signatures in the 3.3- to 3.9-micron region. As outlined initially the purpose of the system is to distinguish between oil and water in a fashion that is independent of the surface state of the water. This is accomplished by performing the two wavelength reflectance measurement as described in the first part of this section. All view factors are removed by the processing when the two channels are identical in their fields of view.

The reflectance of water is well known and is shown in Figure 18, however, previously the only data available on oil was in the form of transmission (Figure 17). The location of the C-H bond absorption in the 3.0- to 3.5-micron region could be interpreted to give an absorption coefficient similar in nature to that shown in Figure 18. An anomalous dispersion curve for the reflectance should result as indicated in Figure 18.

In order to optimize the signature difference, the exact shape of the reflectance curves had to be determined. This was done by using the MOD 1 system and substituting different filters. The results are shown in Figure 32. Rather than take the time to obtain exact reflectance values in which source color and system spectral bandpass was removed, the values have been normalized to the known values for water. The resulting oil curve is plotted in Figure 33. The data is for aged crude oil; hence, the signature is not as strong as for a fresh product. It was necessary to use the aged product since a time period of approximately an hour was required to obtain the spectral results.

The above quantities have been processed by hand to simulate the processing signature; ie, the system output. The results are given in Table 6. The implication is that the short wavelength should be 3.3 microns; however, the atmosphere (see Figure 16) is an interfering quantity. Table 7 summarized the atmospheric effects on the signature when the short wavelength values are either 3.3 or 3.4 microns. As can be seen, the system would essentially have to be recalibrated for every range and atmospheric condition (water vapor) if 3.3 microns were used. Hence, 3.4 microns is a better choice even though the signature is lower by 0.14 units.

Also, from the data it appears that 3.9 microns is the optimum long wavelength value. This does not, however,

NOTE: The values are not corrected for source color or system spectral response.

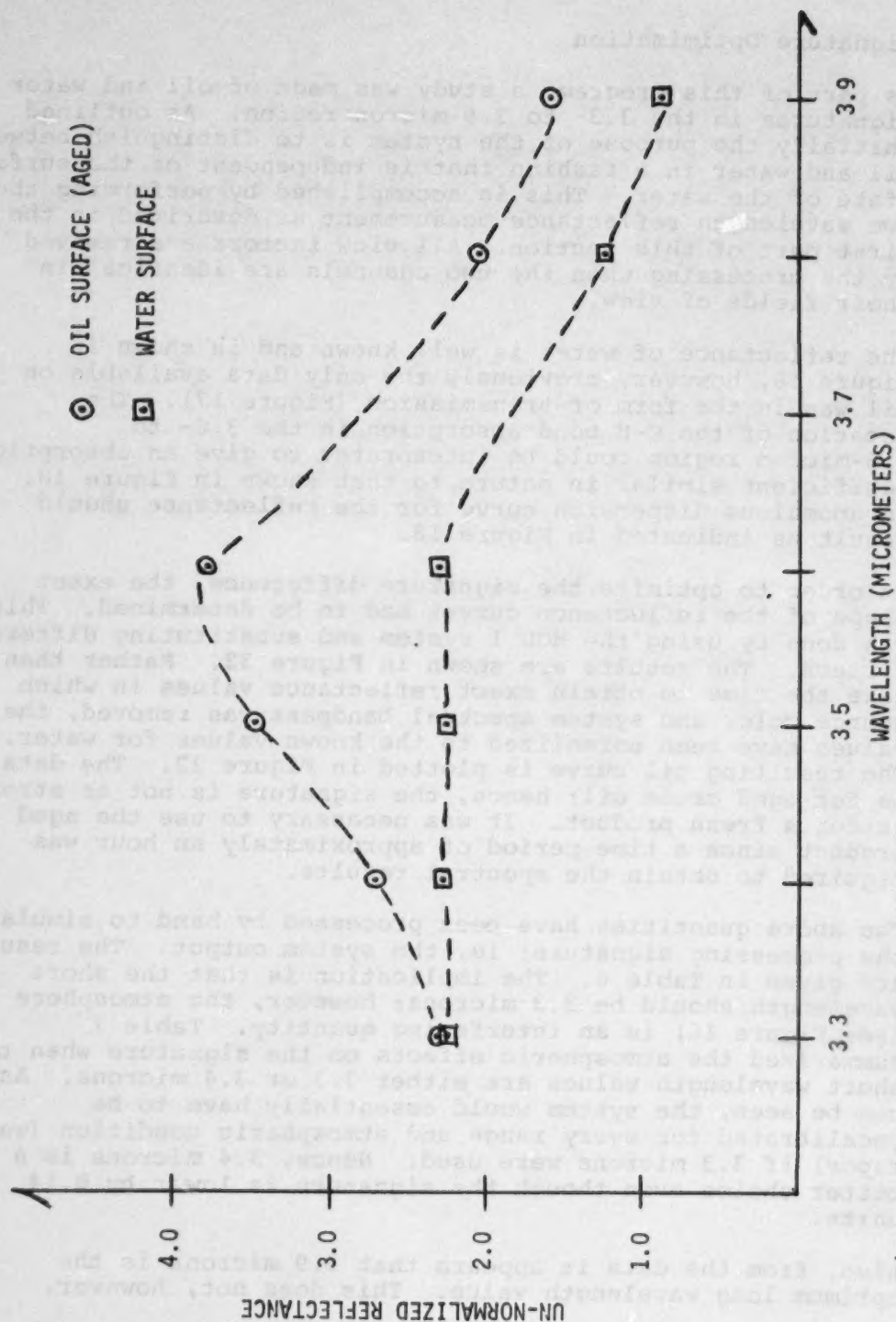


Figure 32. Measured Reflectances from Smooth Oil and Water Surfaces

NOTE: The normalization values were obtained from a water surface and the values in Reference 1.

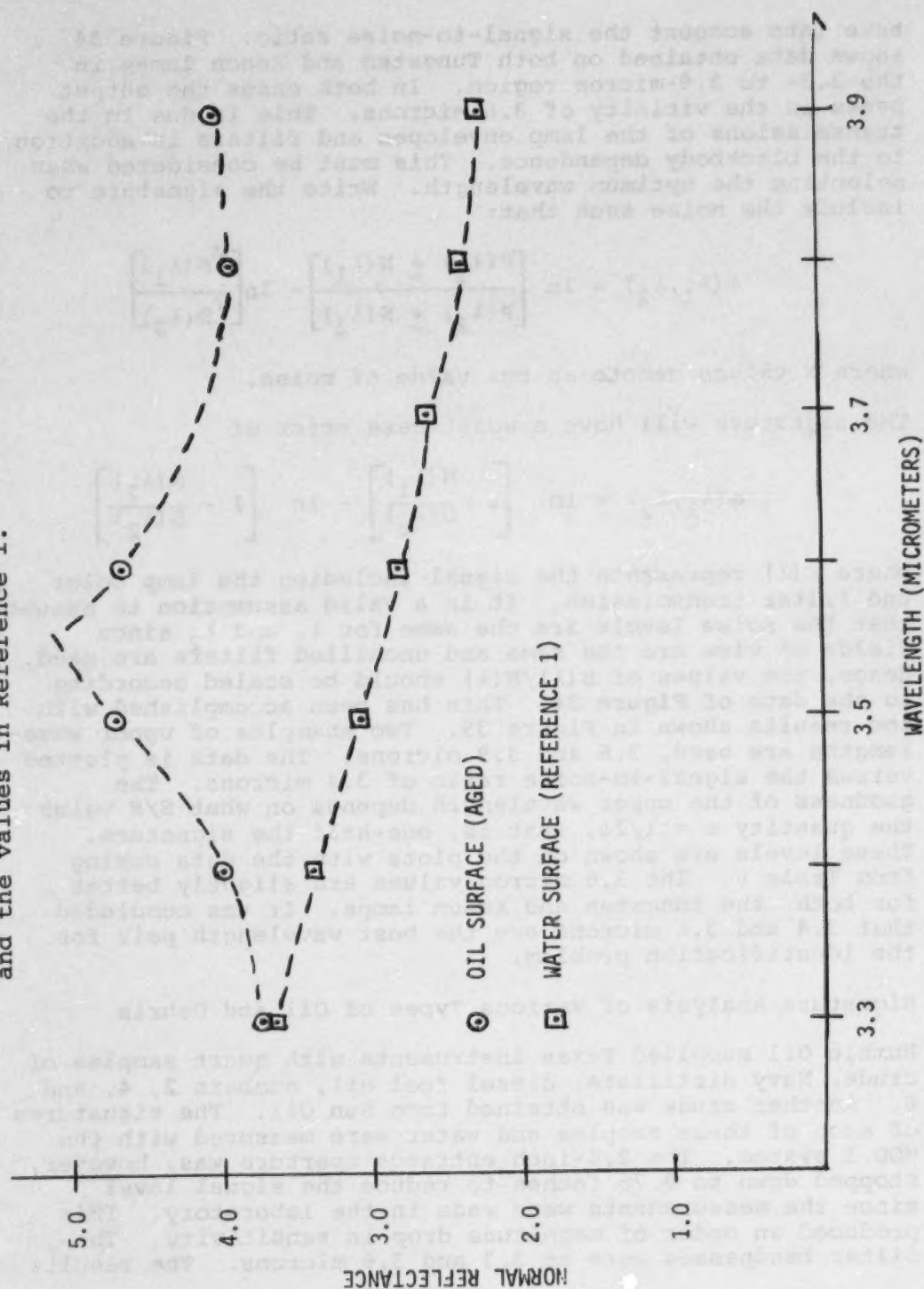


Figure 33. Reflectance from a Smooth Oil Surface at Normal Incidence

take into account the signal-to-noise ratio. Figure 34 shows data obtained on both Tungsten and Xenon lamps in the 3.3- to 3.9-micron region. In both cases the output peaks in the vicinity of 3.6 microns. This is due to the transmissions of the lamp envelopes and filters in addition to the blackbody dependence. This must be considered when selecting the optimum wavelength. Write the signature to include the noise such that:

$$\phi(\lambda_1, \lambda_2) = \ln \left[\frac{P(\lambda_1) \pm N(\lambda_1)}{P(\lambda_2) \pm N(\lambda_2)} \right] - \ln \left[\frac{V_B(\lambda_1)}{V_B(\lambda_2)} \right]$$

where N values denote an rms value of noise.

The signature will have a worst case error of

$$e(\lambda_1, \lambda_2) = \ln \left[1 + \frac{N(\lambda_1)}{S(\lambda_2)} \right] - \ln \left[1 - \frac{N(\lambda_2)}{S(\lambda_2)} \right]$$

where $S(\lambda)$ represents the signal including the lamp color and filter transmission. It is a valid assumption to assume that the noise levels are the same for λ_1 and λ_2 since fields of view are the same and unchilled filters are used. Hence, the values of $S(\lambda)/N(\lambda)$ should be scaled according to the data of Figure 34. This has been accomplished with the results shown in Figure 35. Two examples of upper wavelengths are used, 3.6 and 3.9 microns. The data is plotted versus the signal-to-noise ratio of 3.4 microns. The goodness of the upper wavelength depends on what S/N value the quantity $e = 1/2\phi$, that is, one-half the signature. These levels are shown on the plots with the data coming from Table 6. The 3.6 micron values are slightly better for both the tungsten and Xenon lamps. It was concluded that 3.4 and 3.6 microns are the best wavelength pair for the identification problem.

Signature Analysis of Various Types of Oil and Debris

Humble Oil supplied Texas Instruments with quart samples of crude, Navy distillate, diesel fuel oil, numbers 2, 4, and 6. Another crude was obtained from Sun Oil. The signatures of each of these samples and water were measured with the MOD 1 system. The 2.5-inch entrance aperture was, however, stopped down to 0.75 inches to reduce the signal level since the measurements were made in the laboratory. This produced an order of magnitude drop in sensitivity. The filter bandpasses were at 3.3 and 3.6 microns. The results

NOTE: Xenon Data is for a short arc, small cathode unit operating at 25 μ sec. pulsewidth.

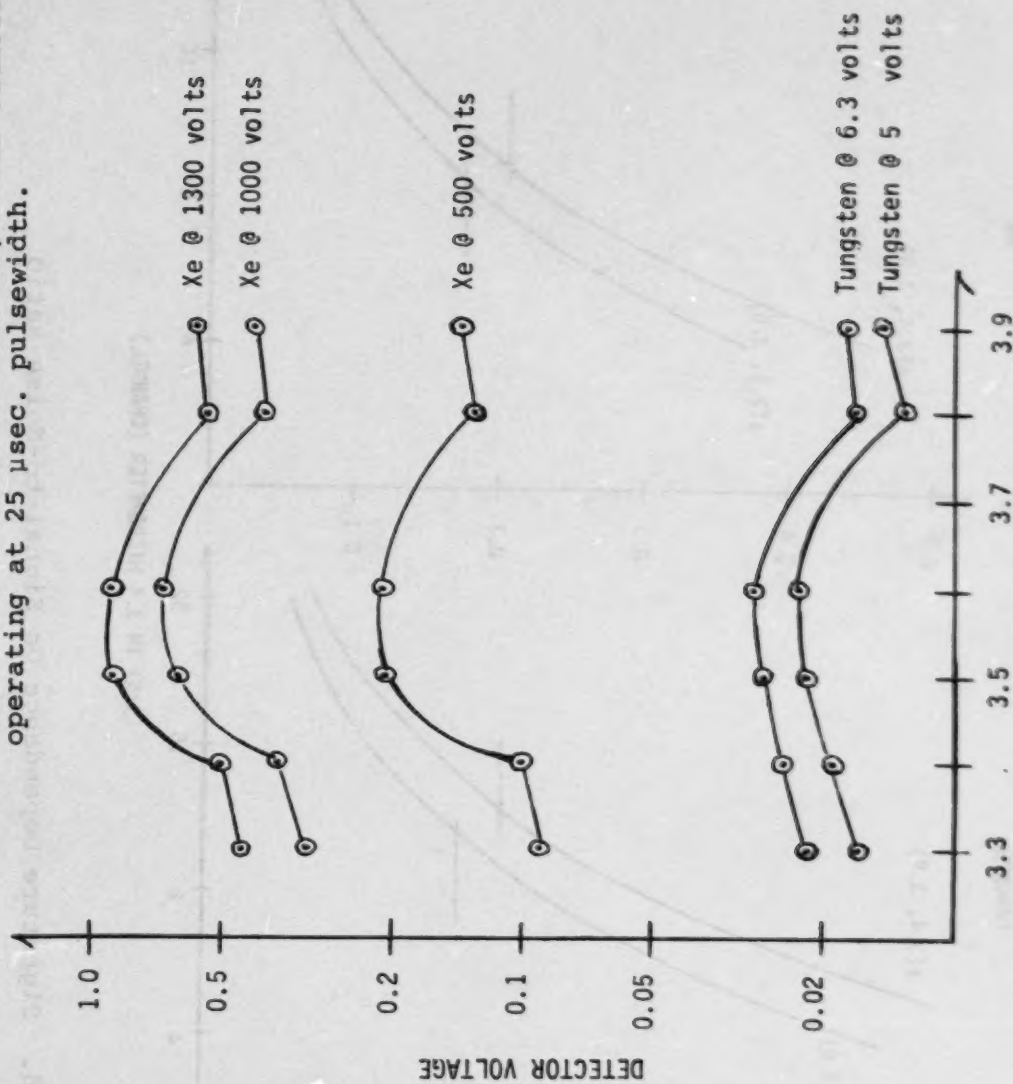


Figure 34. Lamp Output Versus Wavelength

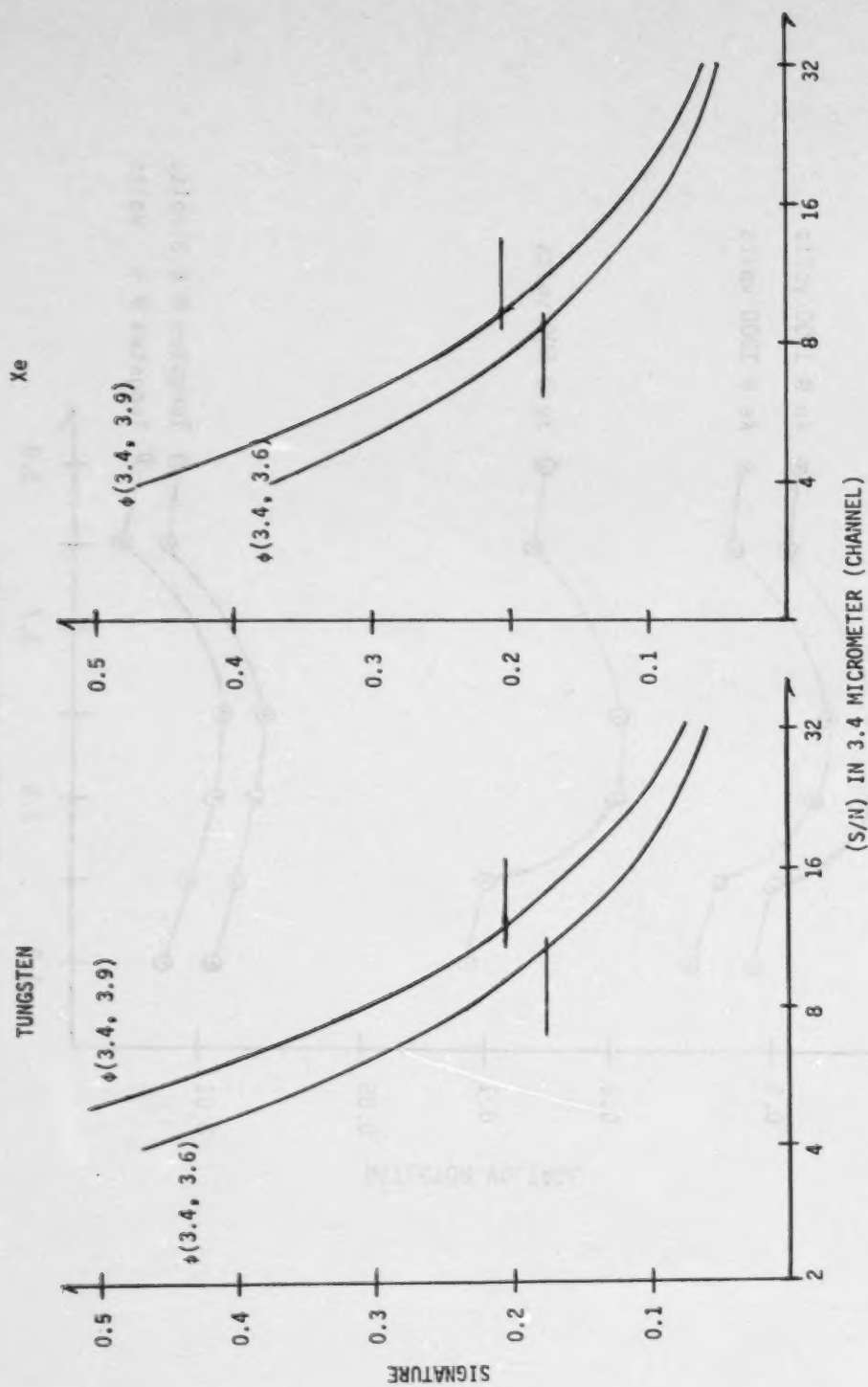


Figure 35. Signature Dependence On Signal-to-Noise Ratio

of the "log difference: signature are given in Table 8. As can be seen, the variation between samples does not exceed 3 percent. This can be considered negligible for this type of application.

For the system to discriminate various types of oil from water is not sufficient for a remote alarm system. The system must also not confuse materials such as dirt, mud, or floating debris with oil. Therefore, the same "log difference" signature was measured for a variety of materials including the above. The MOD 1 system in the same configuration as was used for the oil signatures was again used. The results are shown in Table 9.

TABLE 6. COMPUTER SIGNATURES VERSUS WAVELENGTH

λ (μm)	(3.3 μm , λ)			(3.4 μm , λ)		
	WATER	OIL	DIFFERENCE	WATER	OIL	DIFFERENCE
3.3	-	-	-	-.08	+.06	-.14
3.4	.08	-.06	.14	-	-	-
3.5	.18	-.23	.41	.10	-.17	.27
3.6	.27	-.22	.49	.19	-.16	.35
3.7						
3.8	.44	-.04	.48	.36	.02	.34
3.9	.48	-.07	.55	.40	-.01	.41

TABLE 7. ATMOSPHERIC EFFECTS

	3.4 μm	3.3 μm
τ (600 FT)	0.72	0.96
Log Transmission	-.33	-.04

TABLE 8. SIGNATURES FOR SIX TYPES OF OIL
AND WATER

<u>Sample</u>	<u>ϕ (3.3μm, 3.6μm)</u>
Water	0.41
Crude (Humble)	-0.04
Navy Distillate	-0.07
Diesel #2	-0.07
Fuel #4	-0.04
Fuel #6	-0.04
Crude (Sun Oil)	-0.04

TABLE 9. SIGNATURES FOR VARIOUS TYPES OF DEBRIS, WATER AND
CRUDE OIL

<u>Sample</u>	<u>V(3.3μm) (Volts)</u>	<u>V(3.6μm) (Volts)</u>	<u>ϕ (3.3μm, 3.6μm)</u>
Water	0.70	1.57	+0.41
Oil	0.72	2.55	-0.13
Dirt	0.019	0.016*	+1.30
	0.018	0.018*	+1.13
Mud	0.045	0.080	+0.58
Dirt with Oil	0.018	0.021*	-1.12
Plywood	0.018	0.018*	+1.13
Plywood with Oil	0.013	0.047	-0.16
Plywood with Water	0.53	1.10	+0.41
Paper	0.017	0.017*	+1.13

*Voltage approach noise level of system in apertured mode.

The actual voltages were measured at the point prior to the log amplifiers. The voltages are included in the table to point out the very low value of reflectance of soil and plywood primarily at the 3.6-micron wavelength. The result is that in terms of this system concept, paper, dirt and plywood give a signature value even more positive than does

water. In fact, for those values indicated by the asterisk, the 3.6-micron voltage approached the noise level of the MOD 1 system with its 0.75-inch aperture and resulting decreased sensitivity. There was also a drop in the 3.3 micron values although not as pronounced. This latter point is attributed to the diffuse nature of the reflection.

In addition to the above, natural alga was checked as a potential false alarm. The material used was that which was found as naturally occurring at the edges of the pond at the Texas Instruments test site. The alga had a signature which was indistinguishable from water. Hence, it will not false alarm the system.

SECTION VI

DEMONSTRATION SYSTEM, PASSIVE SENSOR

General System Description

The system employed for the passive infrared (IR) oil spill sensor demonstration was a Multipurpose Infrared System (MIRS) developed by Texas Instruments for the Night Vision Laboratories. This system, designed for use as a night sight, has a direct view raster display produced with light emitting diodes. The primary considerations for design of the MIRS were weight and power consumption. Effective performance and low cost were also important design goals. Staying within design limits required many trade-offs in terms of cooling, electronics, optics, and water tightness; therefore, the system may not have been ideal for the purposes of the oil spill investigative study. This sensor, however, was sensitive in the 8- to 14- micron region, had good thermal resolution, and could demonstrate the feasibility of IR oil spill detection and surveillance.

The MIRS weighs 5.4 pounds and uses Mercury-Cadmium-Telluride (HgCdTe) detectors in a straight vertical line array. The system also uses 44 Gallium-Arsenide-Phosphide (GaAsP) light emitting diodes (LED's) in the same array configuration as the detectors. This facilitates reproducing the scene as seen by the detectors. The LED display is direct view and is scanned by one side of the two-sided scan mirror.

The system produces a framing-type presentation. That is, it continuously scans relatively small areal section of the panorama at one time. However, the presentation is a real-time television-type raster scan. Conventional line scanners present video for film or magnetic tape recording of continuous information, one scan line at a time. The MIRS system scan mirror provides the X axis of areal coverage while the array of detectors provides the Y axis. The overall MIRS system is shown in Figures 36 and 37. Figure 38 shows how the MIRS operates.

The detector array receives a frame of IR energy with a field of view (FOV) of 5° vertical and 10° horizontal. The following paragraphs describe how the MIRS operates.

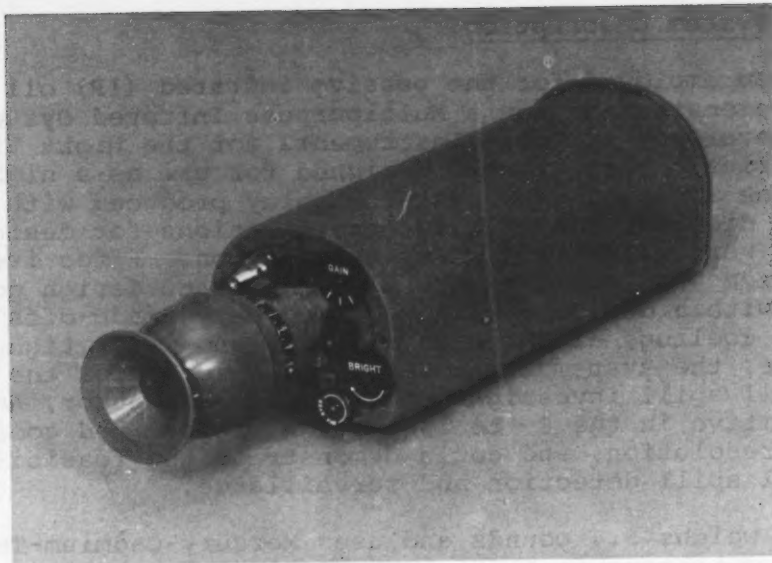


Figure 36: Multipurpose Infrared System

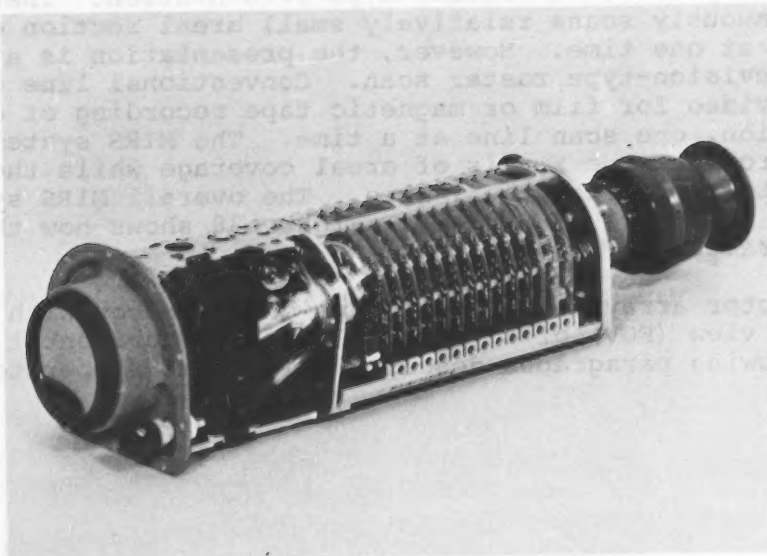


Figure 37: MIRS Optics and Electronics Packaging

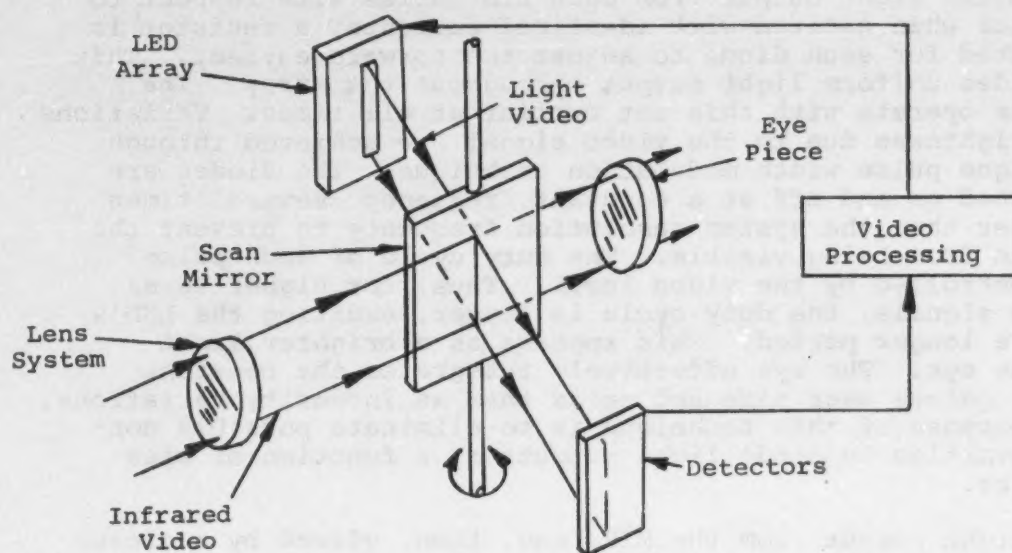


Figure 38: MIRS Concept Design

With the system pointed in one direction, infrared energy, proportional to the scene pattern, passes through a lens system to a two-sided scan mirror. The scan mirror oscillates through an angle of 20° about a vertical axis; thus, the energy reflects from the mirror with an oscillation in the X-Y plane of 20° . The IR energy pattern is then focused on a vertical line array of 44 detectors. As the IR pattern oscillates, the detector line array sweeps out the entire IR input with each half cycle of oscillation. The detector line array has a relative horizontal movement with respect to the IR pattern. This type of configuration produces a bi-directional scan.

The video signal from each detector is processed and applied to the associated LED on the vertical array of 44 Gallium Arsenide Phosphide (GaAsP) LED's. The LED output reflects from the opposite side of the two-sided scan mirror, through a lens system, to the eyepiece.

On each half cycle of scan oscillation, the scan mirror is tilted to shift the IR pattern vertically by 0.01 inches. At the same time, the light array on the opposite side is shifted in the opposite vertical direction by the same amount. This is called interlacing, and produces 88 lines per frame of video.

Since the light output from each LED varies with respect to another when excited with identical currents, a resistor is selected for each diode to adjust the forward current. This provides uniform light output throughout the array. The diodes operate with this set current at all times. Variations in brightness due to the video signal are achieved through a unique pulse width modulation technique. The diodes are switched on and off at a constant frequency several times greater than the system resolution frequency to prevent the pulses from being visible. The duty cycle of each pulse is controlled by the video level. Thus, for higher level video signals, the duty cycle is longer, exciting the LED's over a longer period. This appears as a brighter light to the eye. The eye effectively integrates the constant level pulses over time and reads them as intensity variations. The purpose of this technique is to eliminate possible non-uniformities in diode light outputs as a function of bias current.

The light output from the MIRS was, then, viewed by a closed circuit TV camera which facilitated presentation on a remote monitor and allowed video tape recording of the data. For accurate measurement of voltage level differences between oil and water, one of the 44 channels of video was diverted into the video input of an oscilloscope, where polaroid photographs of one channel of video were taken.

The system of cooling used for the HgCdTe detectors is an open cycle, Joule-Thompson, cryogenic cooler, using compressed Nitrogen gas to accomplish cooling at 77°K (-321°F).

Spatial and Thermal Resolution

The modulation transfer function (MTF) of an electro-optical system simply shows the system relative response as a function of spatial frequency. The concept is analogous to that used in the communication field, since many optically oriented systems essentially perform the function of information transmittal. The optical transfer function of the electro-optical equipment corresponds to the electronic transfer function of communication equipment. Each relates the frequency response of a system to an input source of energy which, in the case of IR imaging systems, is a point source.

As is the case for electronic transfer functions, the total system MTF is composed of the MTF's of the various individual components. Results of the theoretical calculations of the MTF for the MIRS is shown in Figure 39. Modulation,

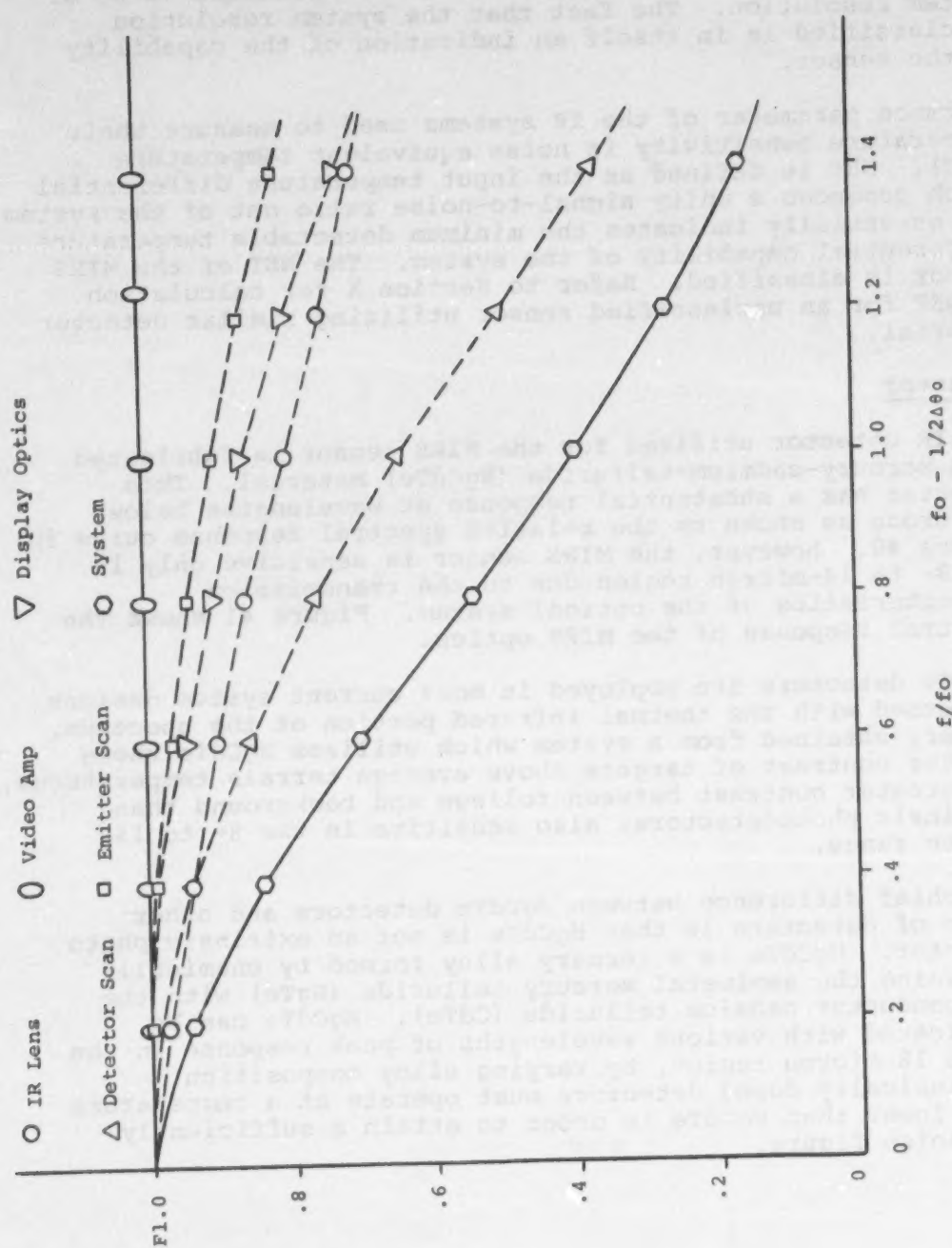


Figure 39. System MTF

normalized to 100%, is plotted as a function of spatial angular resolution and normalized to the specified value of system resolution. The fact that the system resolution is classified is in itself an indication of the capability of the sensor.

A common parameter of the IR systems used to measure their temperature sensitivity is noise equivalent temperature (NET). NET is defined as the input temperature differential which produces a unity signal-to-noise ratio out of the system. NET essentially indicates the minimum detectable temperature differential capability of the system. The NET of the MIRS sensor is classified. Refer to Section X for calculation of NET for an unclassified sensor utilizing similar detector material.

Detector

The IR detector utilized for the MIRS sensor is fabricated from mercury-cadmium-telluride (HgCdTe) material. This detector has a substantial response at wavelengths below 8 microns as shown by the relative spectral response curve in Figure 40. However, the MIRS sensor is sensitive only in the 8- to 14-micron region due to the transmission characteristics of the optical system. Figure 41 shows the spectral response of the MIRS optics.

HgCdTe detectors are employed in most current system designs concerned with the thermal infrared portion of the spectrum. Imagery obtained from a system which utilizes HgCdTe shows greater contrast of targets above average terrain temperatures, and greater contrast between foliage and background than extrinsic photodetectors, also sensitive in the 8- to 14-micron range.

The chief difference between HgCdTe detectors and other types of detectors is that HgCdTe is not an extrinsic photo detector. HgCdTe is a ternary alloy formed by chemically combining the semimetal mercury telluride (HgTe) with the semiconductor cadmium telluride (CdTe). HgCdTe can be fabricated with various wavelengths of peak response in the 4- to 18-micron region, by varying alloy composition. Extrinsic doped detectors must operate at a temperature much lower than HgCdTe in order to attain a sufficiently low noise figure.

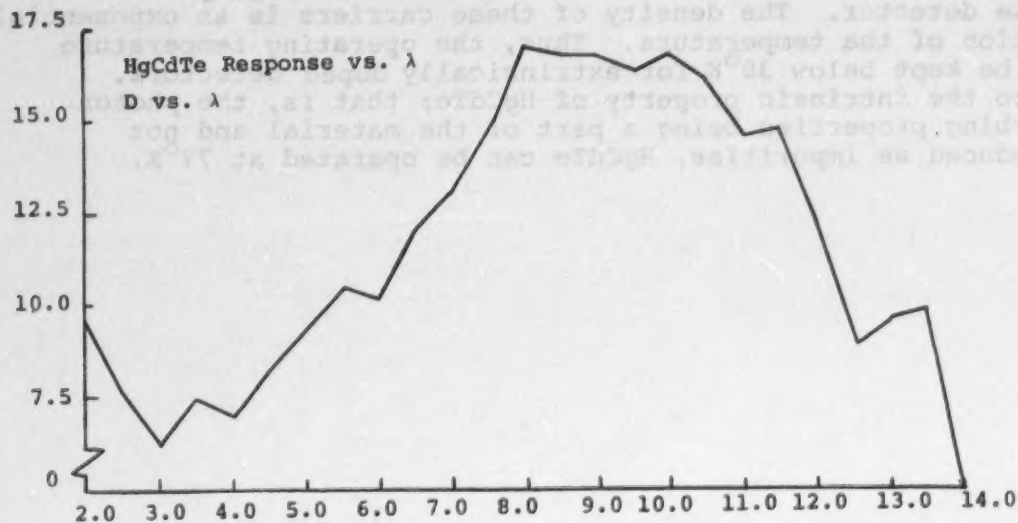


Figure 40. HgCdTe Relative Spectral Response

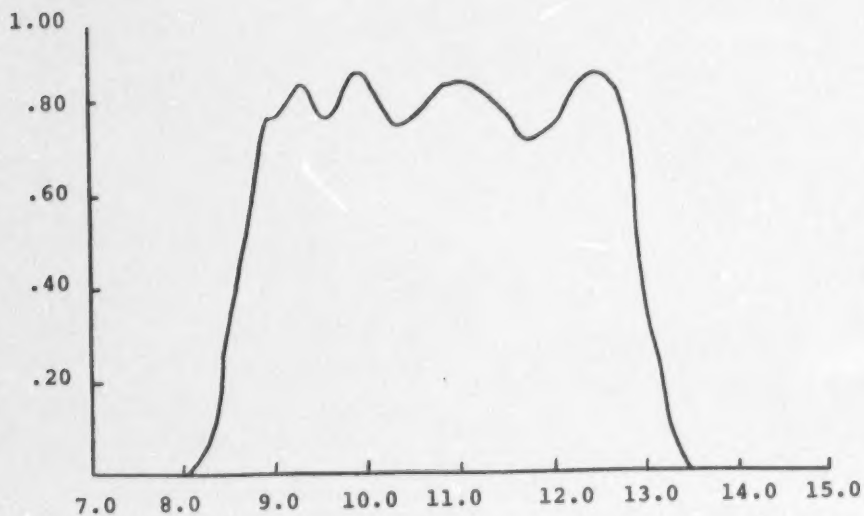


Figure 41. Spectral Response of MIRS Optics

The reason is that the number of free carriers present in the conduction band of an extrinsically doped semiconductor directly affect the magnitude of the noise voltage produced by the detector. The density of these carriers is an exponential function of the temperature. Thus, the operating temperature must be kept below 30°K for extrinsically doped detectors. Due to the intrinsic property of HgCdTe ; that is, the photon absorbing properties being a part of the material and not introduced as impurities, HgCdTe can be operated at 77°K .



Figure 10. Noise voltage spectral response

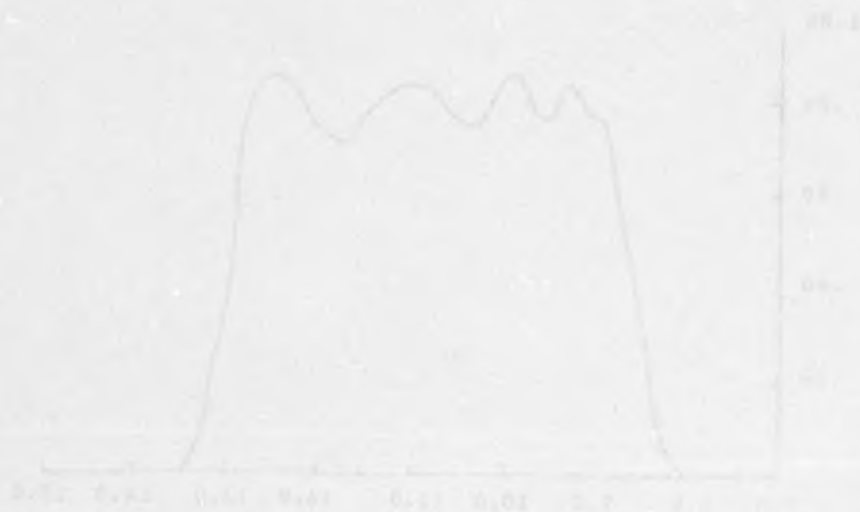


Figure 11. Spectral response of HgCdTe

SECTION VII

TEST RESULTS, ACTIVE SENSOR

The purpose of this test program was to determine experimentally the full capabilities and potentials of the active system. The system demonstrated its capability to absolutely discriminate oil from water, debris, and other similar material. The system was proved to be inexpensive and easy to maintain. In addition, its remote alarm capability was demonstrated. Day or night operation independent of weather and water surface state were also demonstrated to a height of up to 91 feet above the surface. This data was extrapolated to show capability up to 300 feet.

In addition to the above characteristics, the active system, which was proposed as a staring system, whose line of sight was normal to the water surface, is also capable of being operated in a scanning pattern. This pattern can have large tilt angles, depending on the wave action of the body of water. Results of these tests are included in this section in roughly the order in which they were obtained. Hence, the development of the sensor capabilities can be followed.

Short Range Tests

The first step in the evaluation of the system and technique was to install the existing system (MOD 1) on a 30-foot tower overlooking a body of water at a Texas Instruments test range near the Dallas Central Expressway site. A photograph of this installation is shown in Figure 42. The purpose of these initial steps was to test the reflectance versus surface state and to evaluate the various system parameters. A three-channel strip recorder was used. It recorded as a function of time the signal amplitudes at 3.4 and 3.9 microns and also the output of the log processor. The output of the log processor indicated a "yes" or "no" state on the presence of oil. This signal can be used to drive a horn, siren, bell, light or other desired alarm mechanism to provide an audible and/or visual signal to a responsible individual located away from the oil spill site.

While these tests were being performed, the long range system was being designed and fabricated. The results of the MOD 1 tests were utilized to improve the design of the long range system. Of particular significance were the human factor considerations, the simplification of the optic alignment and the stabilization of the optical and electronic subsystems.

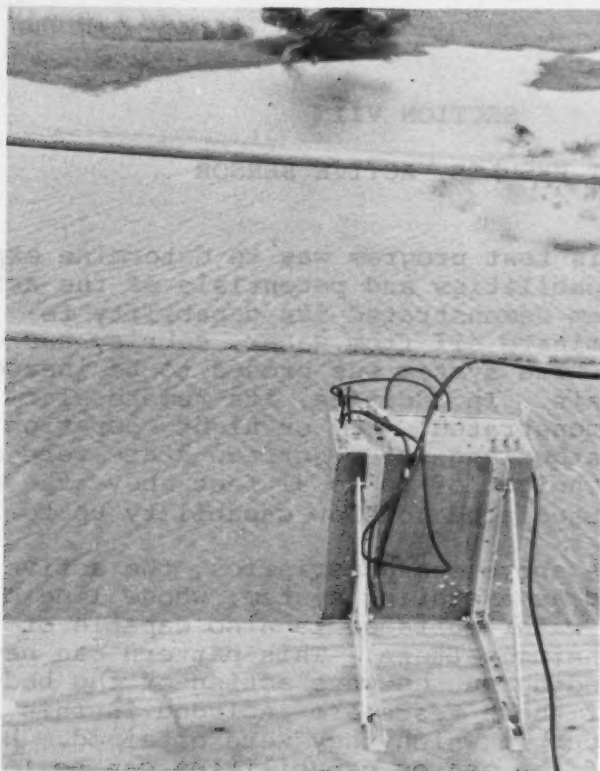


Figure 42. MOD 1 Mounted at 30 Feet Overlooking a Body of Water

Wave Action Data

The primary problem in the field evaluation of the oil spill surveillance system is the scaling of the performance to wave amplitude and period. To determine if the scaling is valid, the signal level prior to the log amplifiers must be correlated to the wave amplitude and period. A probe was built which measures wave amplitude and frequency. An example of the probe output is shown in Figure 43. This data was recorded simultaneously with the other data.

The MOD 1 system was used to evaluate the effects of wave action on the two-channel processing system. Examples of the data are shown in Figures 44 (7 sheets) for MOD 1 system at a height of 30 feet.

The record is for a continuous segment of data. The gains and log amplifiers were set such that the water signature occurred at approximately 70 divisions and the oil at 58 divisions. The actual amplitude of the 3.3- and 3.6-micron channels prior to log processing were also recorded to indicate amplitude fluctuations.

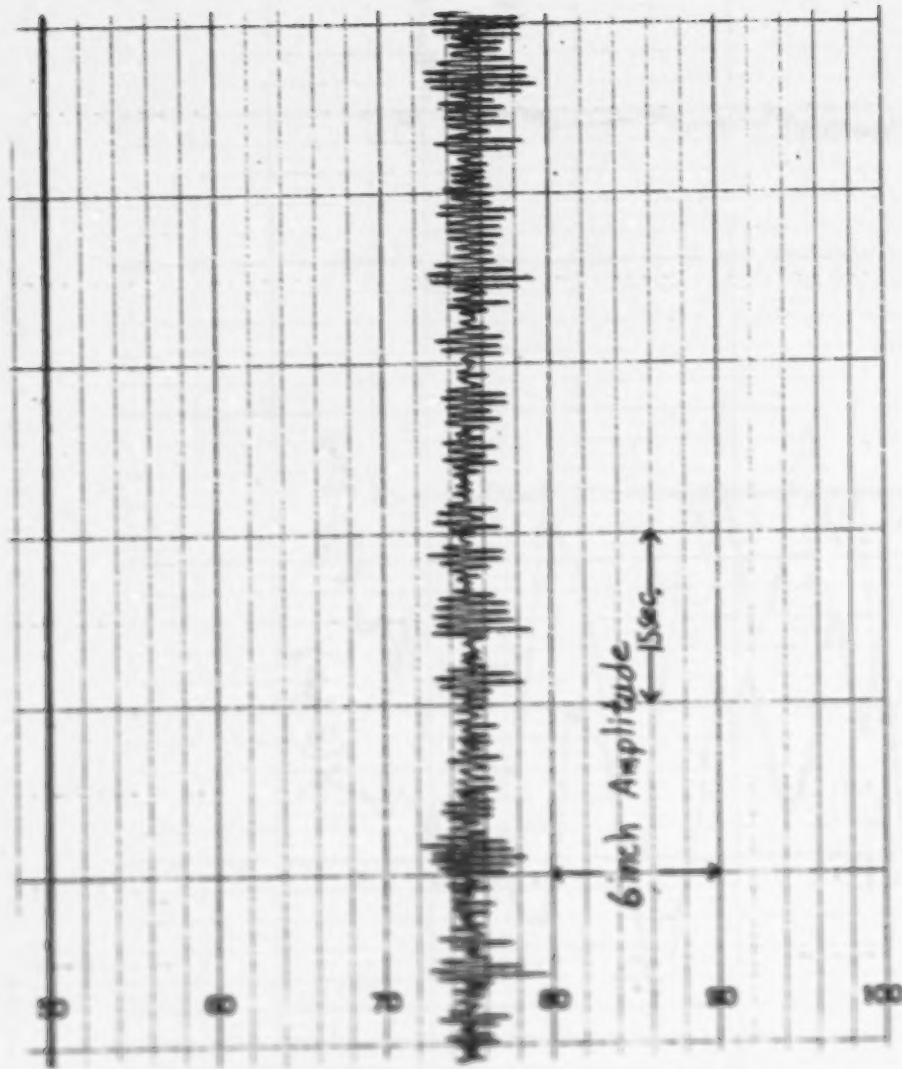


Figure 43. Example of Wave Probe Output

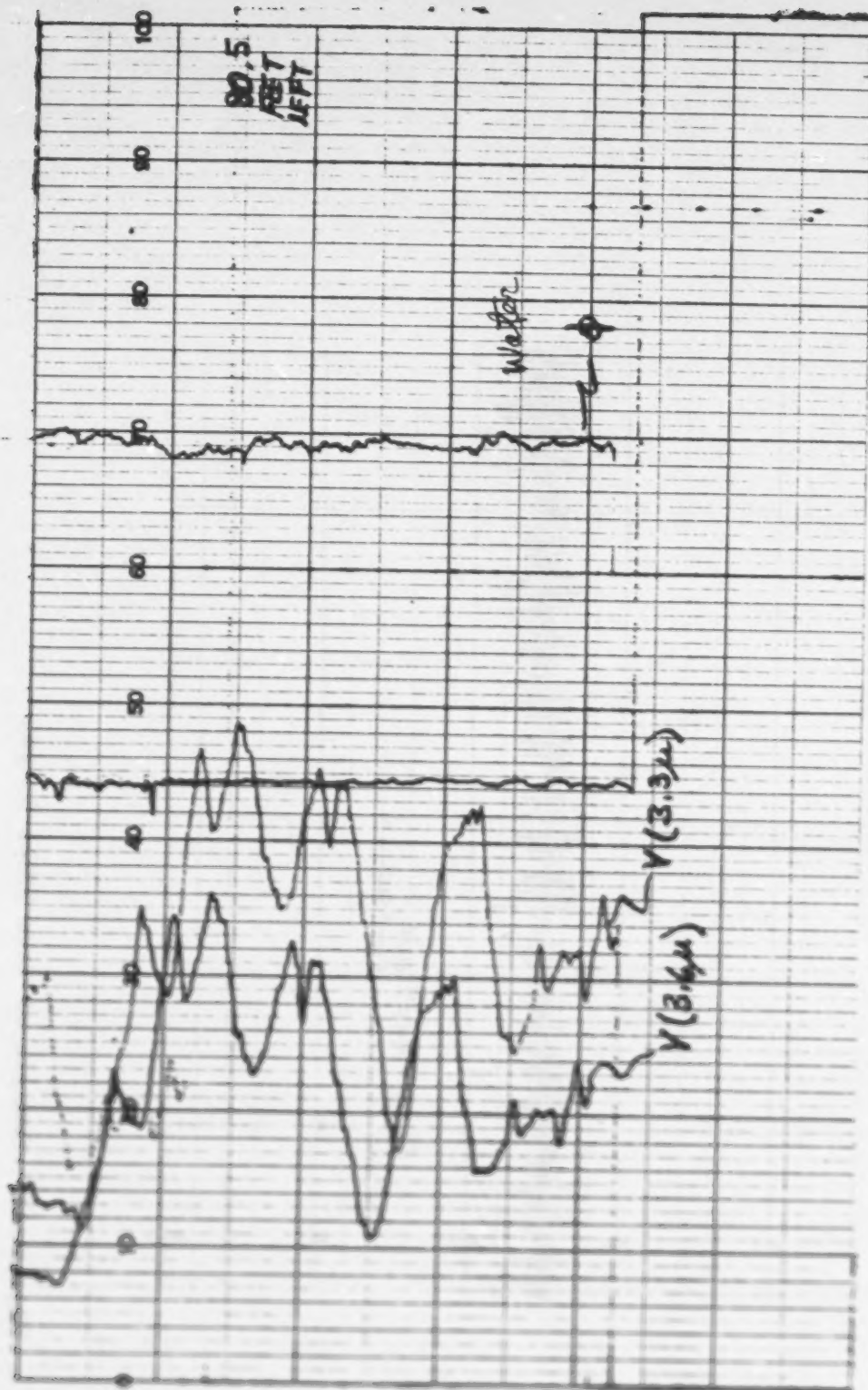


Figure 44. Example of MOD 1 Data at 30 Feet (Sheet 1 of 7)

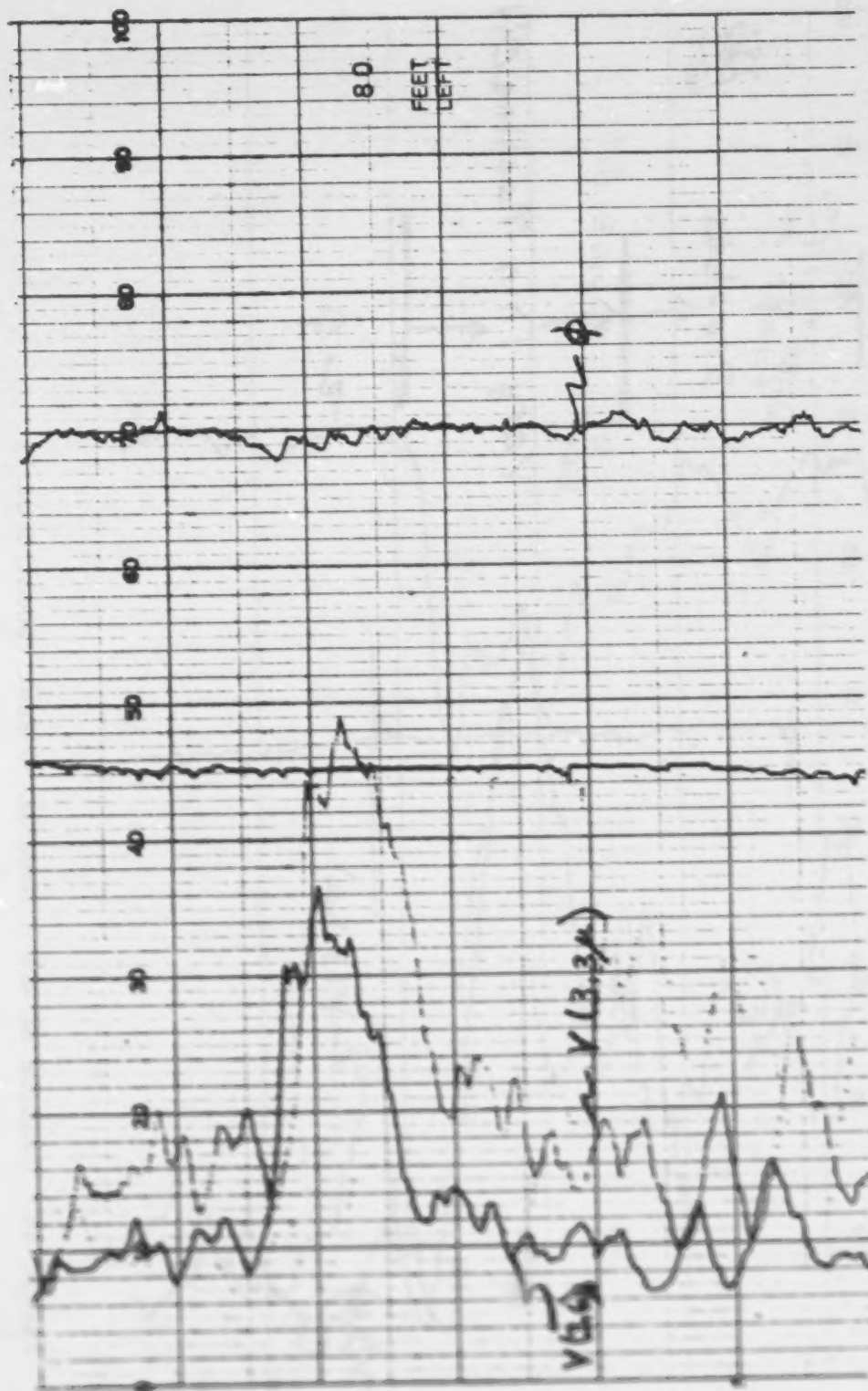


Figure 44. Example of MOD 1 Data at 30 Feet (Sheet 2 of 7)

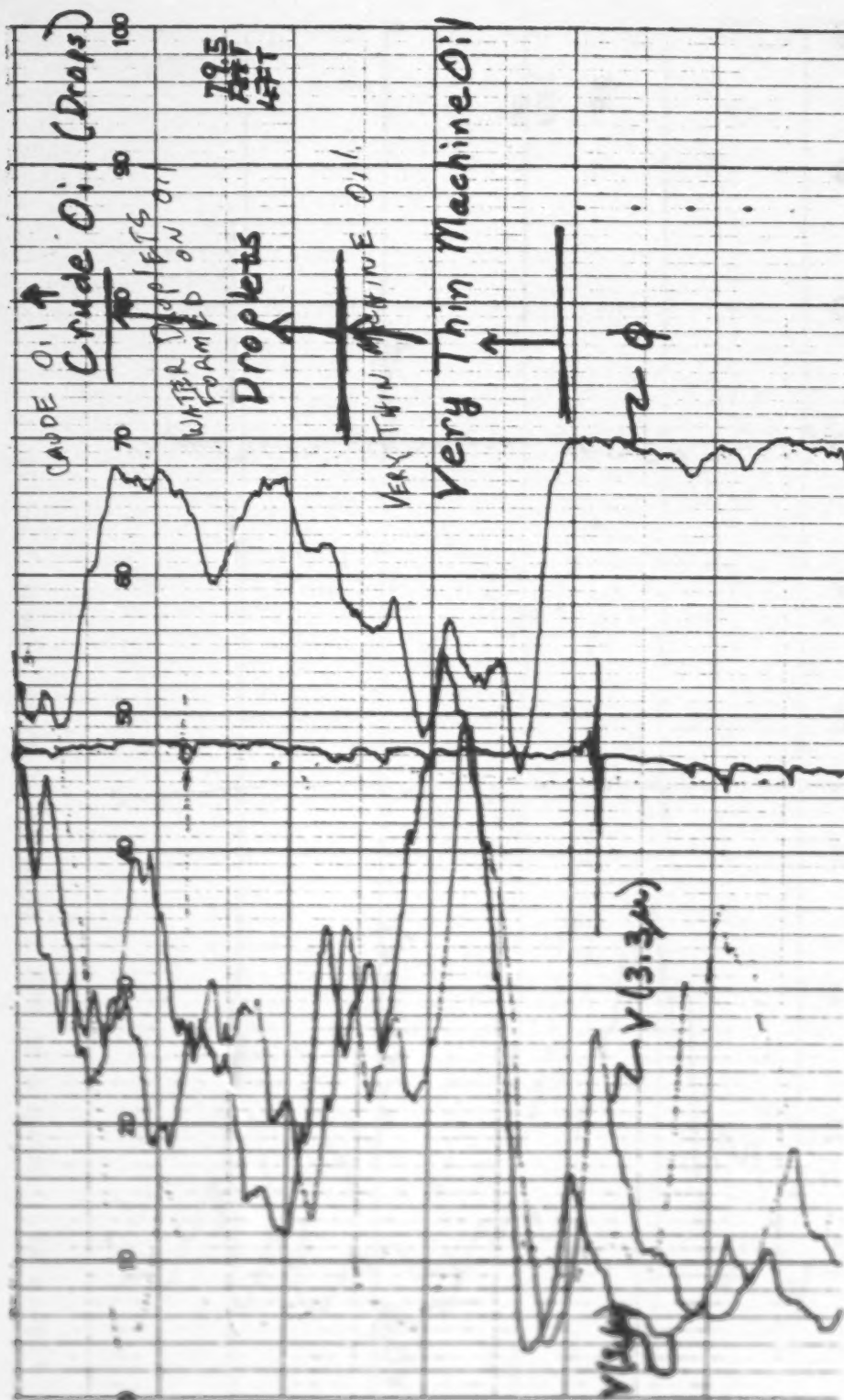


Figure 44. Example of MOD 1 Data at 30 Feet (Sheet 3 of 7)

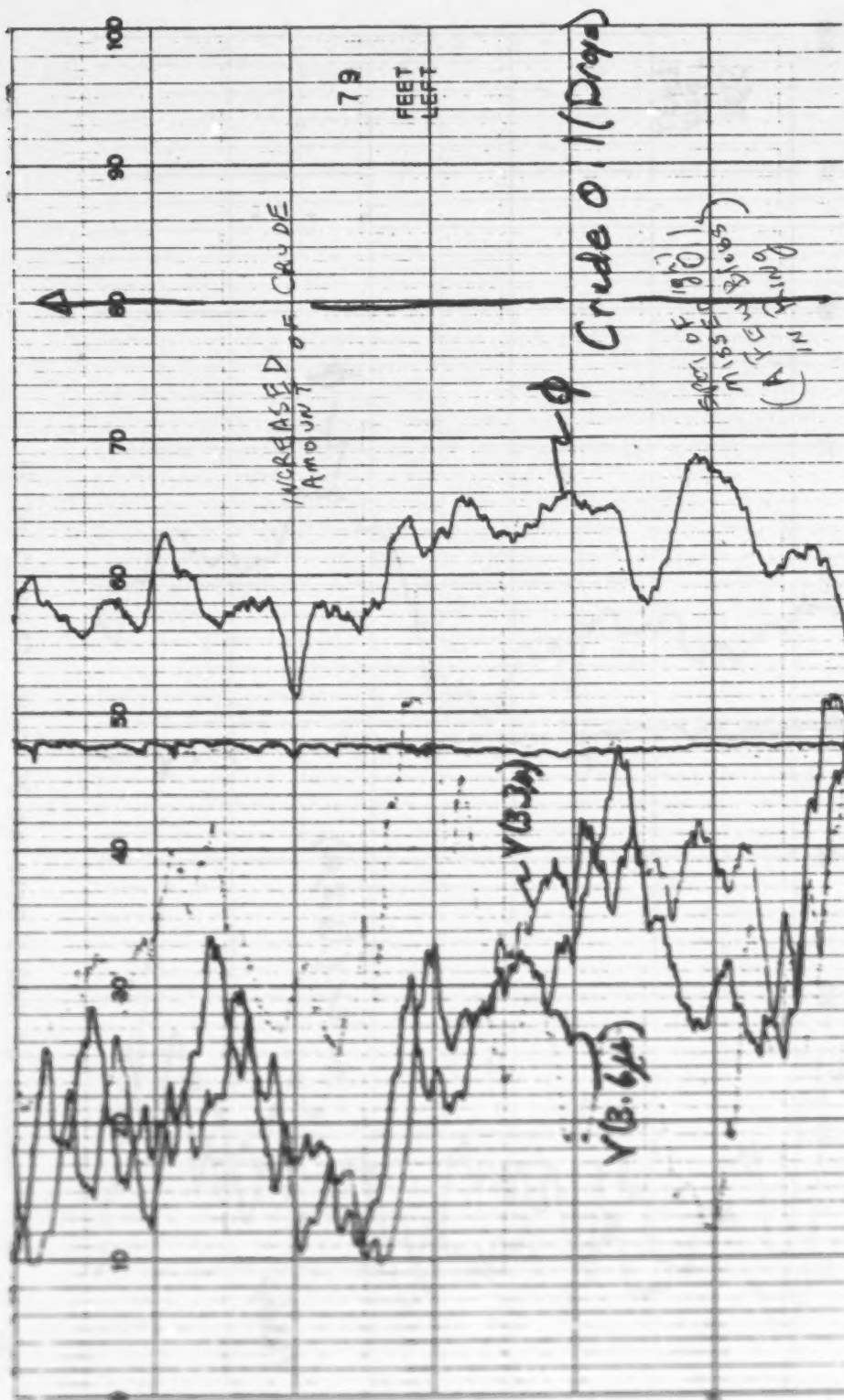


Figure 44. Example of MOD 1 Data at 30 Feet (Sheet 4 of 7)

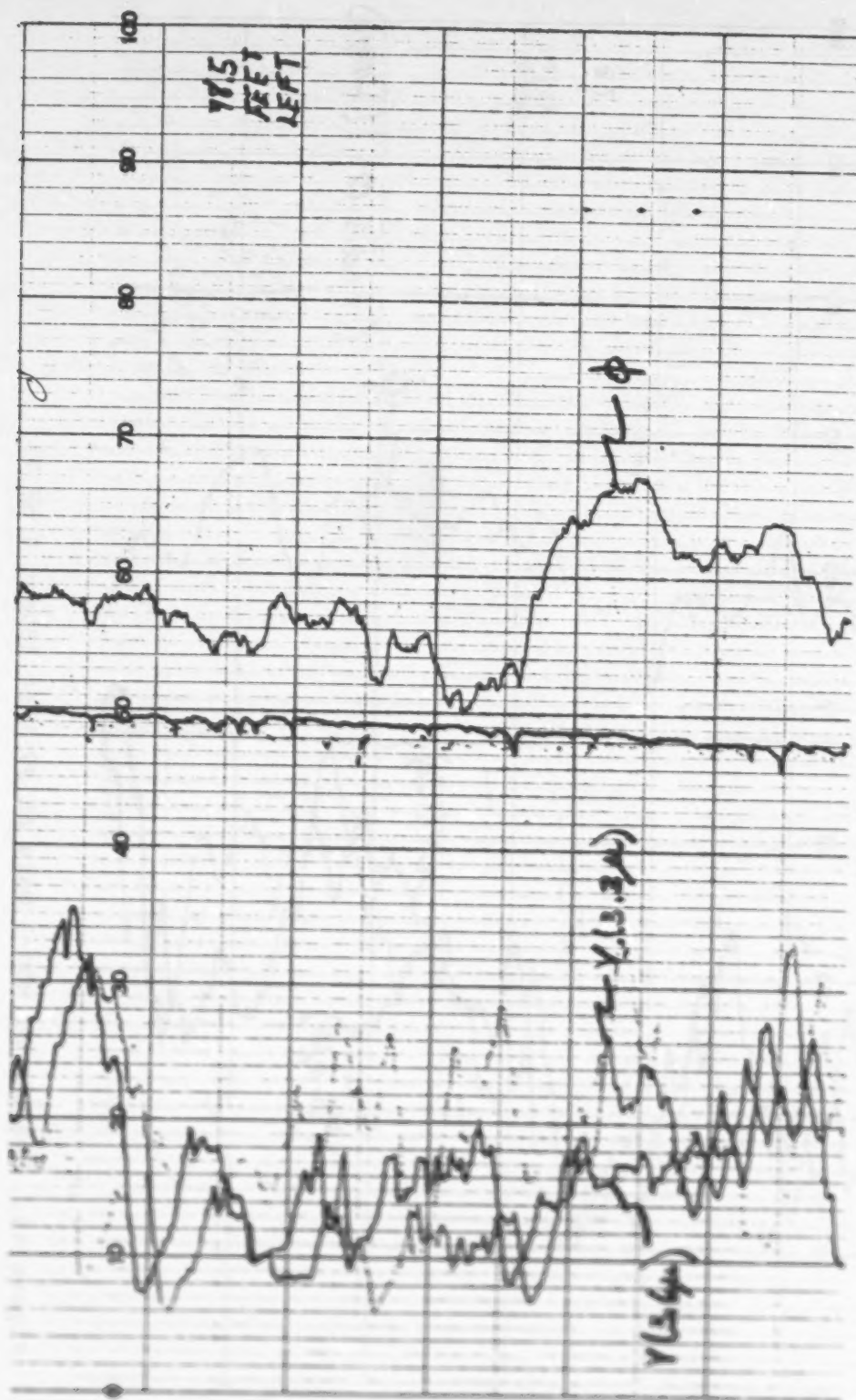


Figure 44. Example of MOD 1 Data at 30 Feet (Sheet 5 of 7)

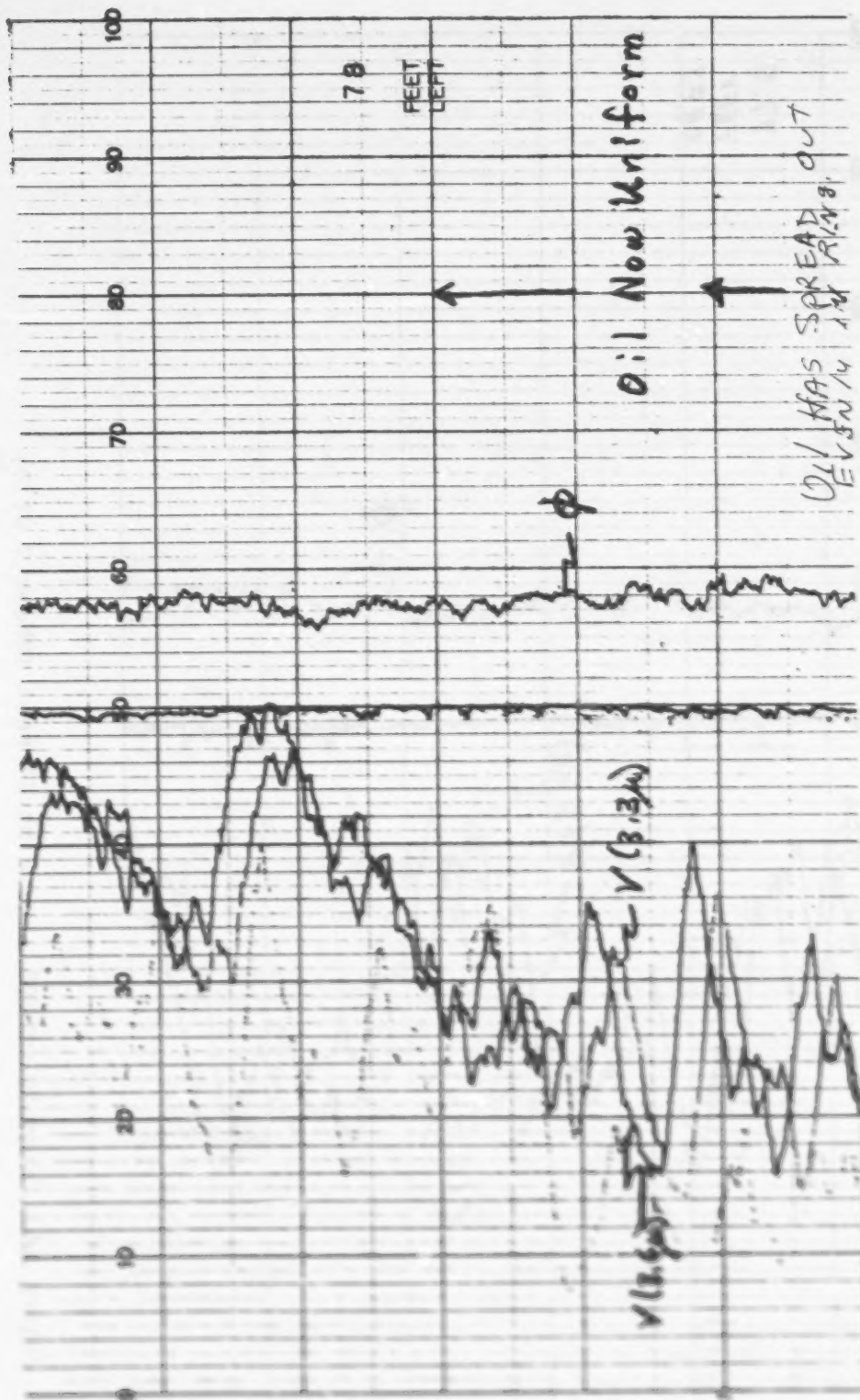


Figure 44. Example of MOD 1 Data at 30 Feet (Sheet 6 of 7)

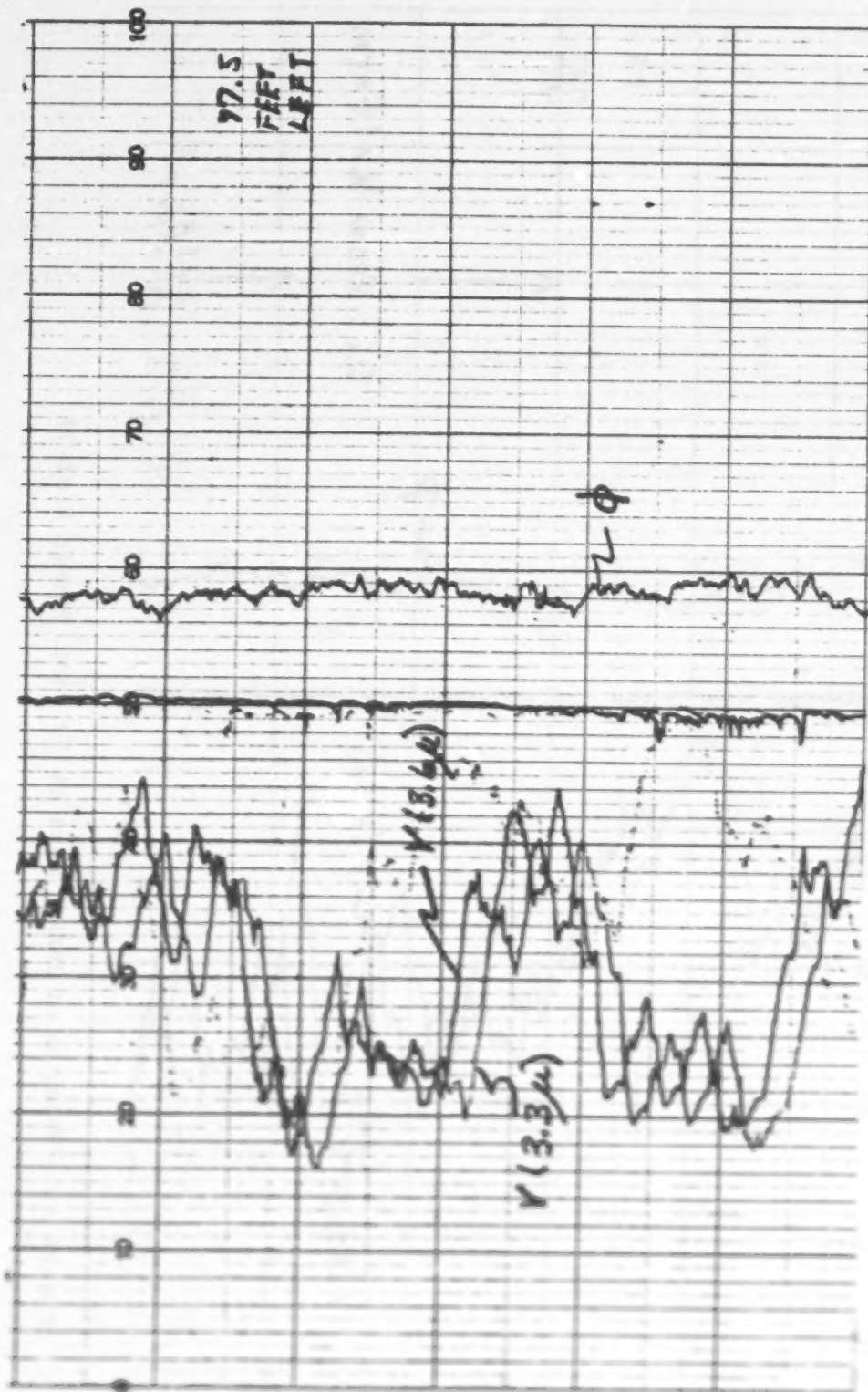


Figure 44. Example of MOD 1 Data at 30 Feet (Sheet 7 of 7)

The systems field of view was on water during the time of Figure 44, sheets 1 and 2. During the time of Figure 44, sheet 3, oil was added to the water surface. At first, light machine oil was used. This condensed into droplets as indicated. Crude oil was then added as noted in the upper portion of Figure 44, sheet 1. The fraction of the water surface within the systems field of view that was covered by the crude oil varied until the surface was uniformly covered as indicated in Figure 44, sheet 6.

The data in Figure 44 exemplifies in terms of signatures the effects of oil covering the water surface in the systems field of view. This data was obtained such that the signal levels of both oil and water targets passed through the same amplitude regions to display signal level independence. The log amplifiers used for this data were an improved design for which the environmental temperature dependence has been reduced.

During the time that the data in Figure 44 was being taken the wave action was that which was naturally occurring on the lake. The average signal level was, therefore, high with the 4 second time constant giving maximum signal variations on the order of 8 to 1. In order to obtain a larger dynamic range, a fan mounted at the base of the tower was turned on to generate increased wave action.

Figure 45 (7 sheets) contains the data for the fan generated waves. Note that the voltage span for this set of data has been increased by an order of magnitude for V(3.6) and V(3.3). Also, the gain of the 3.6 micron channel was increased which repositioned the water signature at 60 divisions and dropped the oil signature to a value of less than 50 divisions. These adjustments are indicated in Figure 45 sheets 1 and 2. During Figure 45, sheet 3, the wave probe was placed on a higher sensitivity. The oil was placed in the systems field of view as shown in Figure 44, sheet 4. The data shown in Figure 45, sheets 5, 6 and 7 demonstrates the discrimination capability of the MOD 1 even under the strong wave action. By comparing the results of Figure 44 with those of Figure 45 it is seen that the demonstrated dynamic range of the MOD 1 system was 50 to 1 using the 4 second time constant.

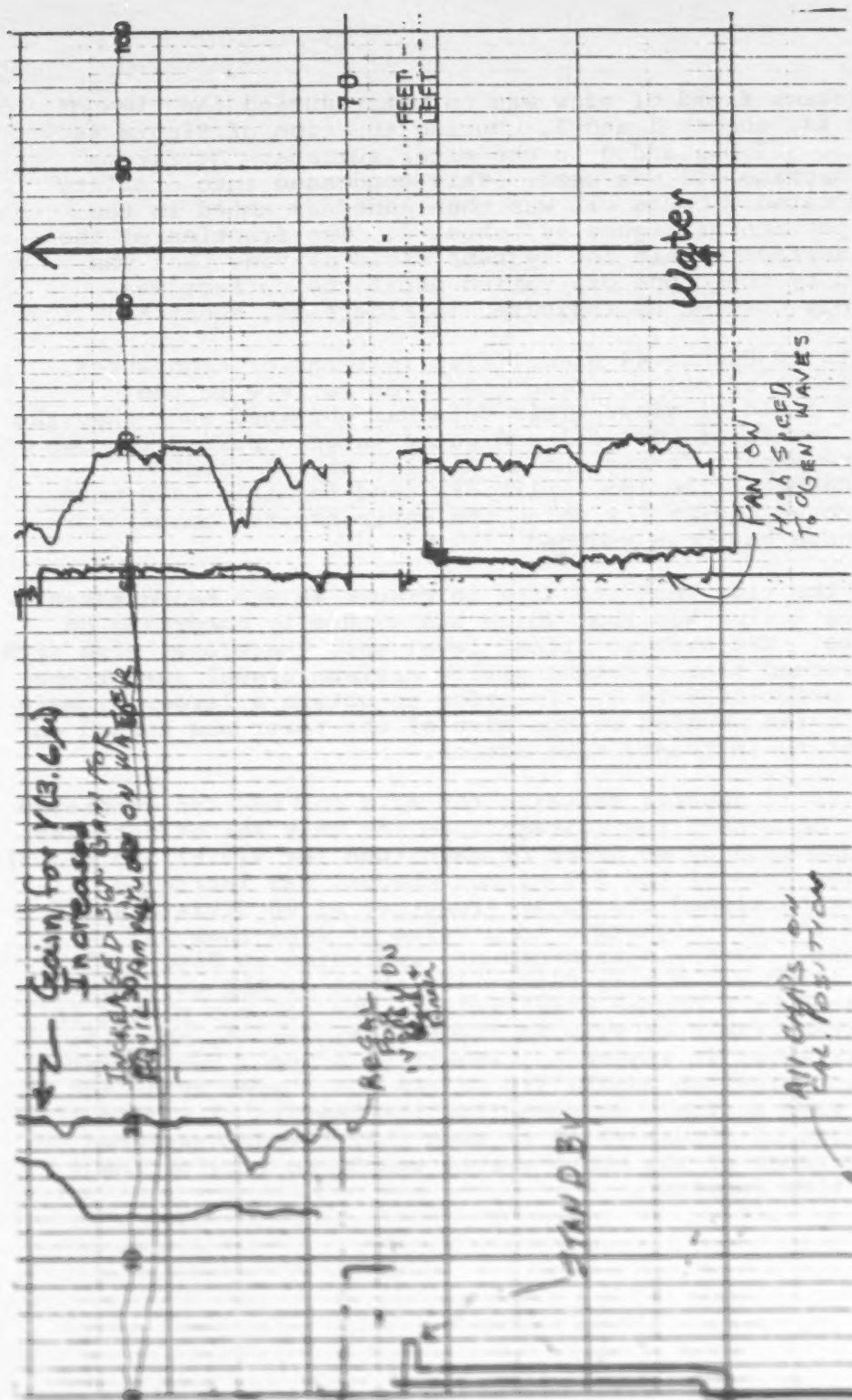


Figure 45. Example of MOD 1 Data with Fan Generated Waves (Sheet 1 of 7)

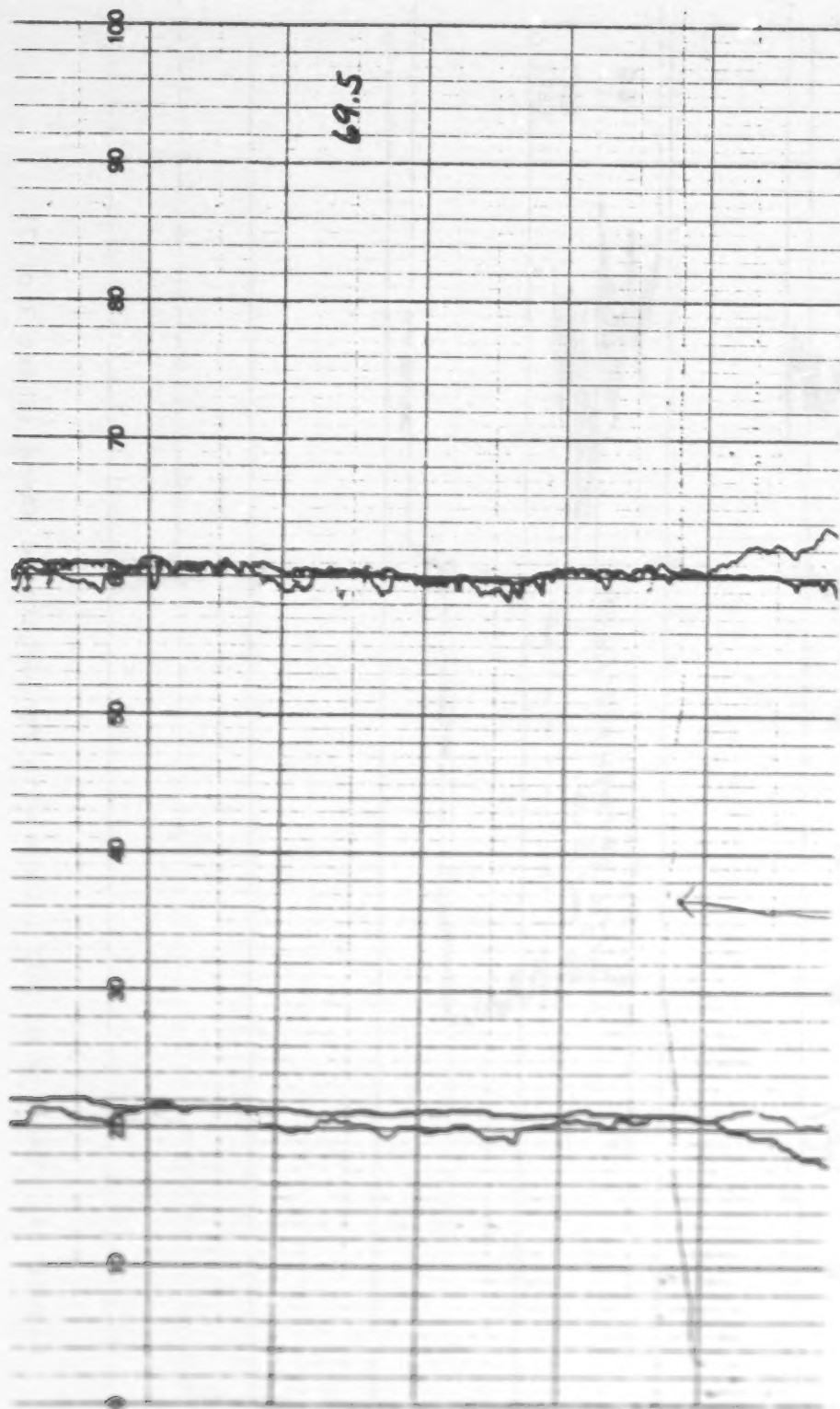


Figure 45. Example of MOD 1 Data with Fan Generated Waves (Sheet 2 of 7)

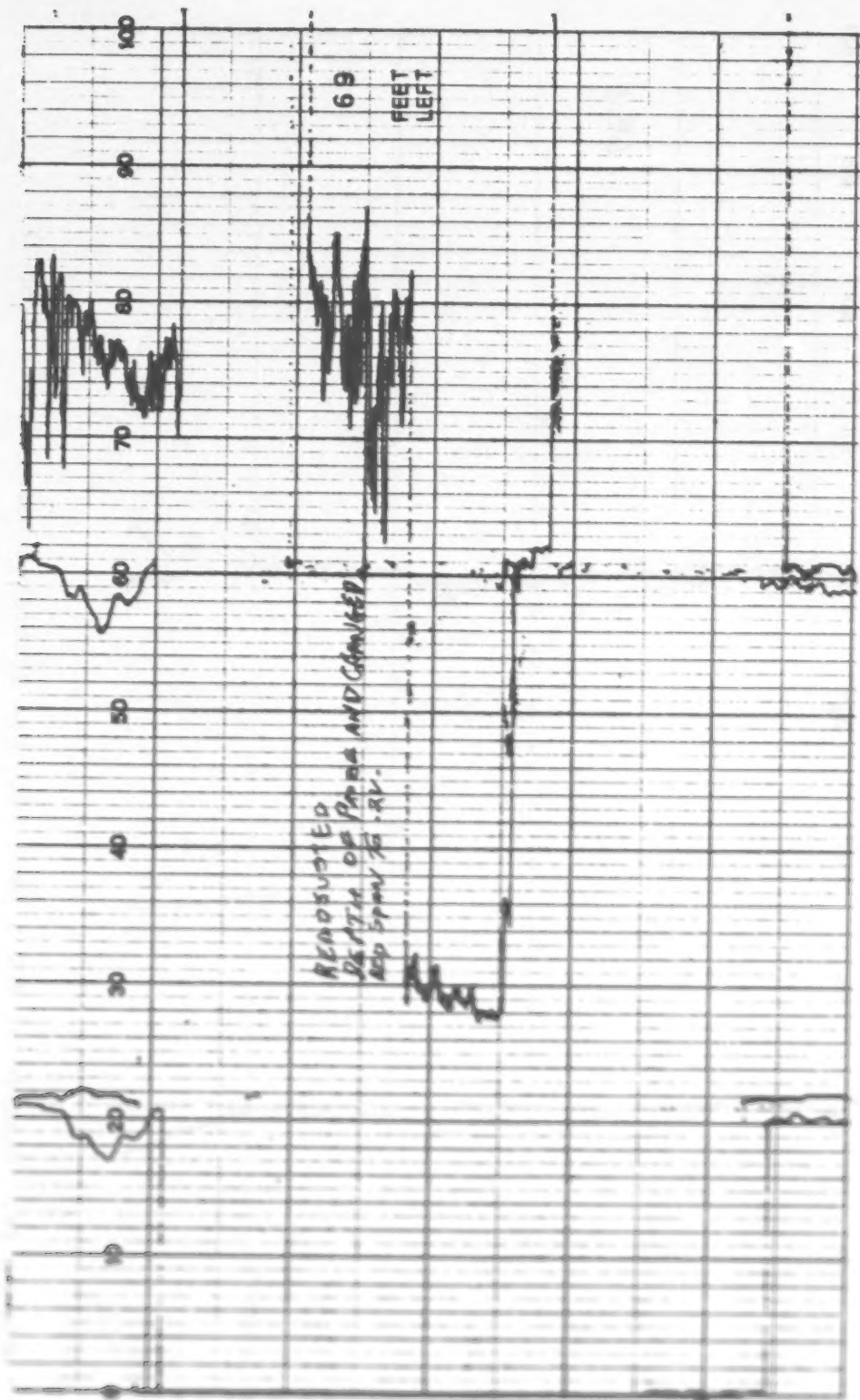


Figure 45. Example of MOD 1 Data with Fan Generated Waves (Sheet 3 of 7)

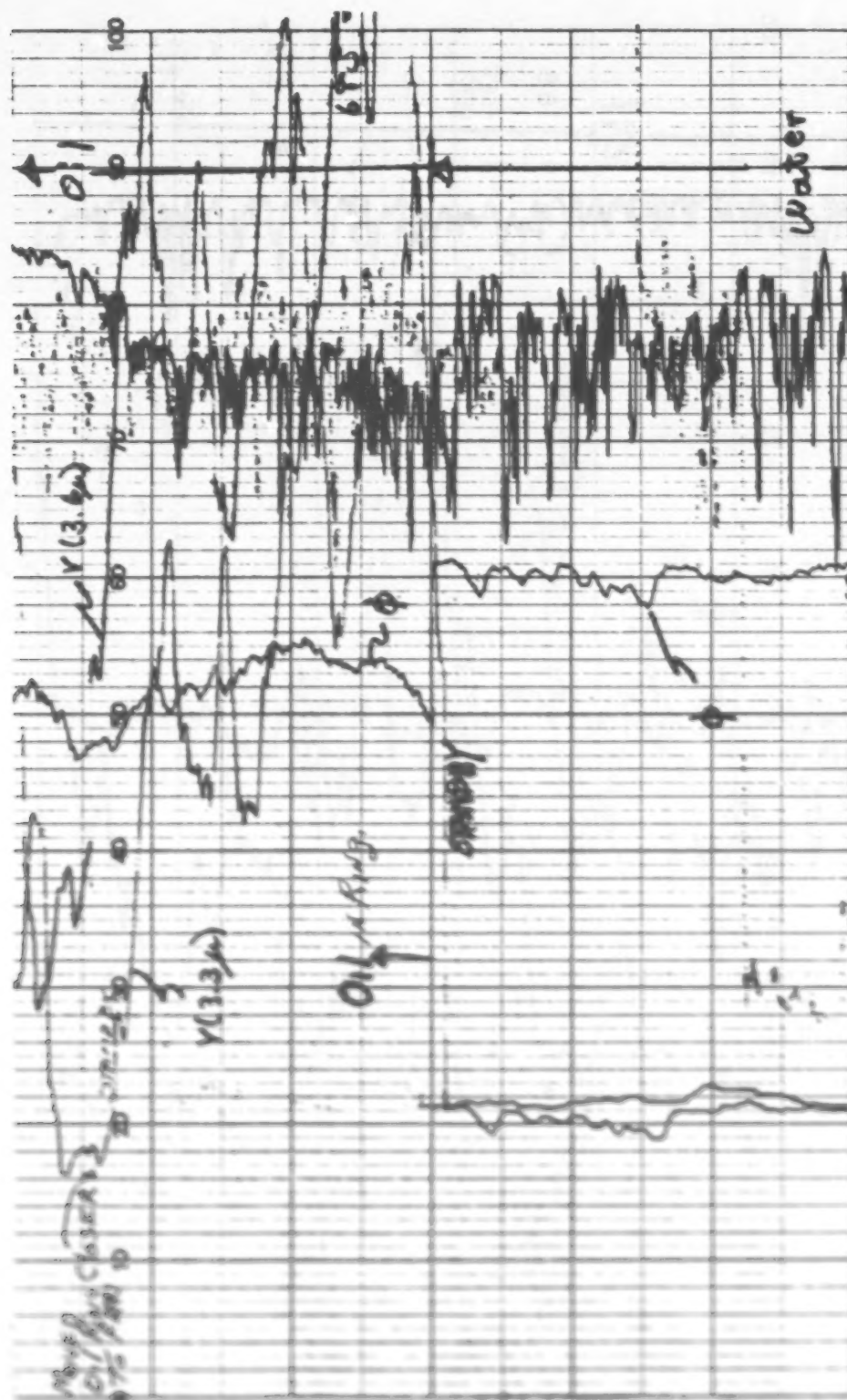


Figure 45. Example of MOD 1 Data with Fan Generated Waves (Sheet 4 of 7)

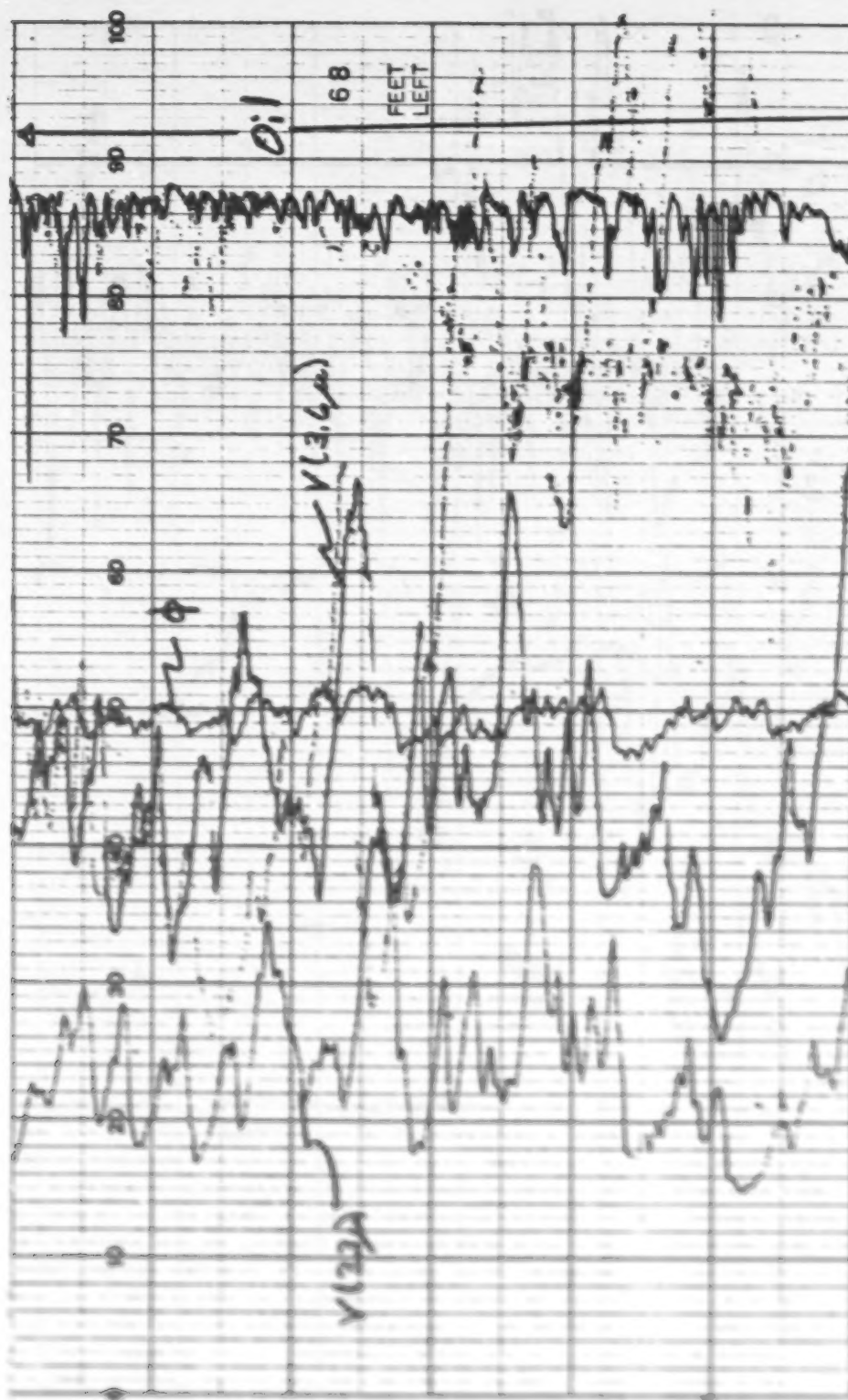


Figure 45. Example of MOD 1 Data with Fan Generated Waves (Sheet 5 of 7)

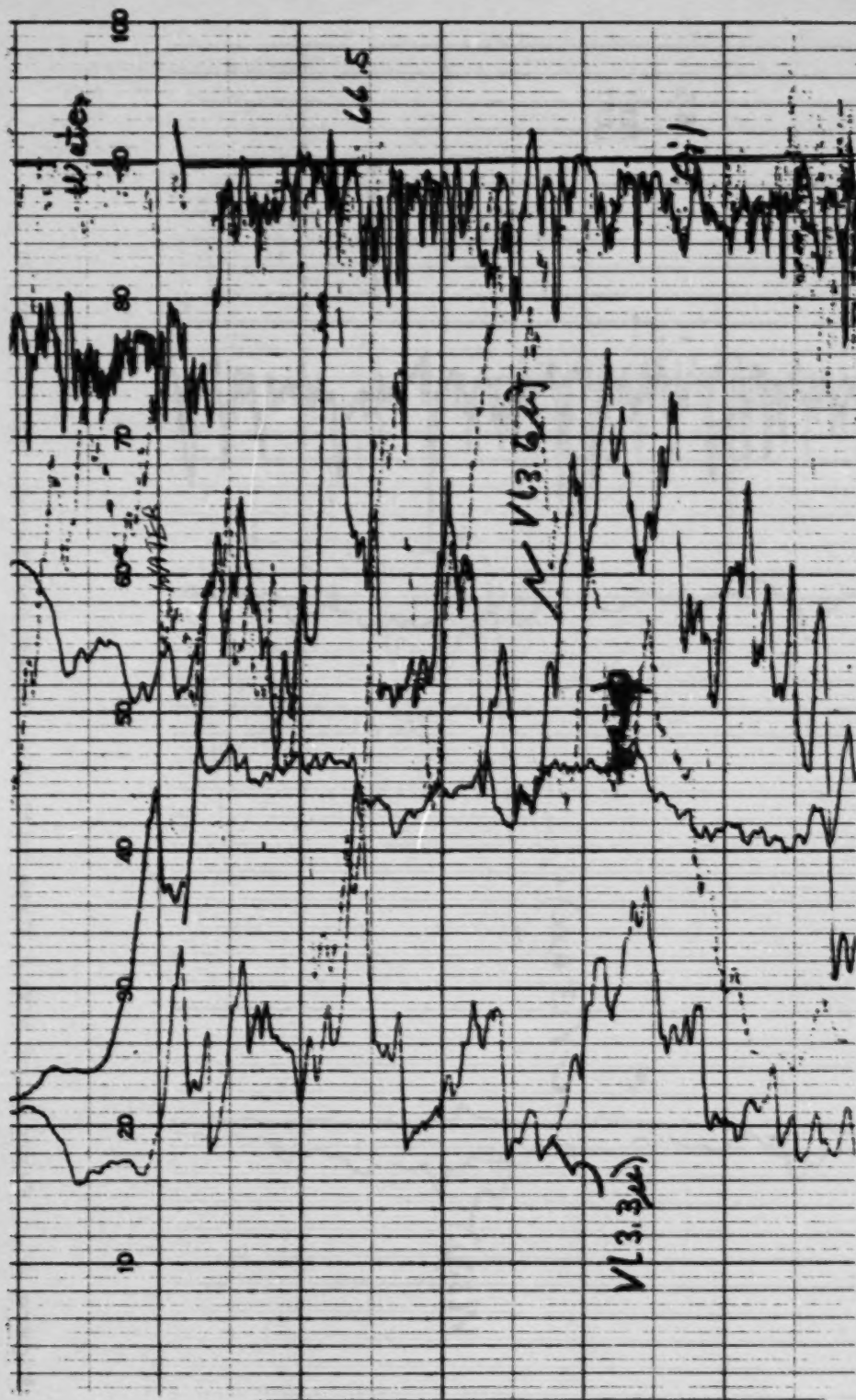


Figure 45. Example of MOD 1 Data with Fan Generated Waves (Sheet 6 of 7)

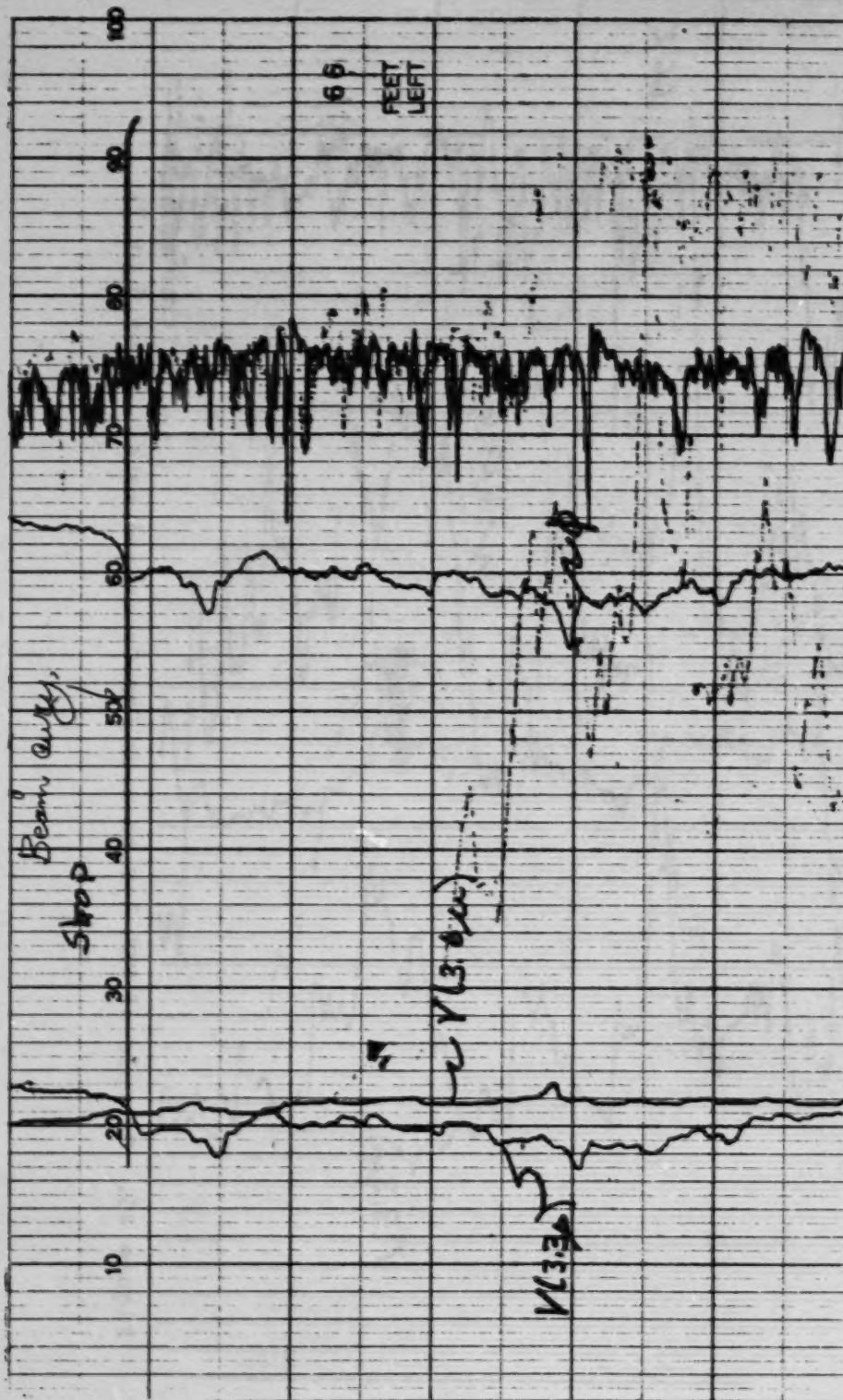


Figure 45. Example of MOD 1 Data with Fan Generated Waves (Sheet 7 of 7)

Angular Data

A key point to the application of an active system is its ability to look at angles off of normal. The degree to which the system can be tilted off of normal will depend on the surface state. The signature or alarm capability will still be independent of the surface state so long as the tilt angle does not exceed some critical value where some signal is lost. It is anticipated that for some surface conditions the optimum view angle is not straight down.

Some preliminary data was taken with MOD 1 system. The wind velocity was 20 mph. The geometry is shown in Figure 46. Note that the angle of wave motion with the scan direction was 45 degrees. Some of the results are shown in Figure 47, sheets 1, 2, and 3. The elevation angle for the data shown in Figure 47, sheet is 2.9 degrees and the target is water. The elevation angle for the data shown in Figure 47, sheets 2 and 3 is 5.7 degrees and the targets are water and oil, respectively. Note that the signatures are valid. The angle subtended by the transmit beam in MOD 1 is approximately 0.5 degrees.

Additional data of this type was taken with the MOD 2 system.

Long Range Tests

MOD 2 Performance

The MOD 2 version of the active system has an approximate 24 milliradian field of view which corresponds to a 1-foot spot at a 50-foot range. The transmitter and receiver each contain a simple lens of focal length 5.90 inches and f/number of 1.5. The anticipated improvement of MOD 2 over MOD 1 was a factor of 16 for a specular reflective surface and a factor of 60 for a Lambertian surface at 30 feet. The specular case could be checked in the laboratory and this criteria was met.

In field operation, the system performed well at the 50-foot test height, implying again that the design goals had been met. This can only be a subjective evaluation due to the nature of wave action on the water surface.

One question which had been raised in program reviews concerned signature dependence on height. The MOD 2 system was set at the 30-foot range and aligned for optimum signal. The system was then moved to the 50-foot height and turned on without any realignment. This corresponded to a 25%

variation in height of sensor above the water surface. The signal level decreased by approximately a factor of 3, but the signature did not change, meaning that the system can satisfactorily operate under these extreme changes.

The theoretical change in going from 30 to 50 feet in height is 2.77 loss in signal. The value cannot be determined exactly due to wave fluctuations, but appears to be closer to a loss of only a factor 2 rather than 3. This implies that the field of view was more optimum for the 1-foot waves at a height of 50 feet than it was at 30 feet.

Some samples of MOD 2 test data are shown in Figure 48, sheets 1 and 2. To record this data the large boom described in a previous section was set under the beam. The log difference was set at 5-V span (0.5 V per major division) with zero position at 3 V; ie, the line 60. At the beginning of the trace, Figure 48, sheet 1 the system was looking at water and the trace shows a slight negative reading at line 55. A small quantity of oil was placed in the boom and the trace dropped to 50. It stayed at approximately this value until a larger quantity of Navy distillate was added, wherein it dropped to 43 and stayed at this value until the oil slick moved away from the beam. Note that the reading did not return to the original reading but remained at 50. This condition was observed for several minutes and did not change until the boom was moved and the water agitated to disperse the scum. Figure 48, sheet 2 shows that the trace then returned to its original water reading of 55. Amplitude settings had to be changed when the boom was removed because of the difference in wave action between inside and outside of the boom and to prevent the recorder, which has a dynamic range of only 10 to 1, from overdriving. However, the log difference output remained the same since the dynamic range of the system is 100 to 1. Another sample of water and oil discrimination is shown in Figure 49, where MOD 2 was viewing the open pond. The oil stayed under the boom approximately 1.5 minutes before natural wave action swept it away.

Angular Data from MOD 2

As first proposed, the active system was to be a staring unit which looked only at the mean normal to the water surface. However, satisfactory systems performance and the knowledge gained concerning wave surfaces prompted the angular scan data discussed in a previous paragraph of this section. More extensive data was obtained with the MOD 2 system.

The data was obtained at both 30- and 50-foot levels. The geometry is shown in Figure 50. Samples of the data are plotted in Figure 51. For this data, all scan angles were along the $\phi = 0$ degree line; ie, in the North direction. The wind was also coming from the North. The plotted values are the signal in the 3.4-micron channel. The signal voltage appears to follow an exponential curve for angles not close to zero. A possible description of the probability of backscatter is

$$P(\theta) = A \left[\frac{\theta}{\theta_0} + B \right]^2 e^{-\theta/\theta_s}$$

for $0 \leq \theta < \pi/2$

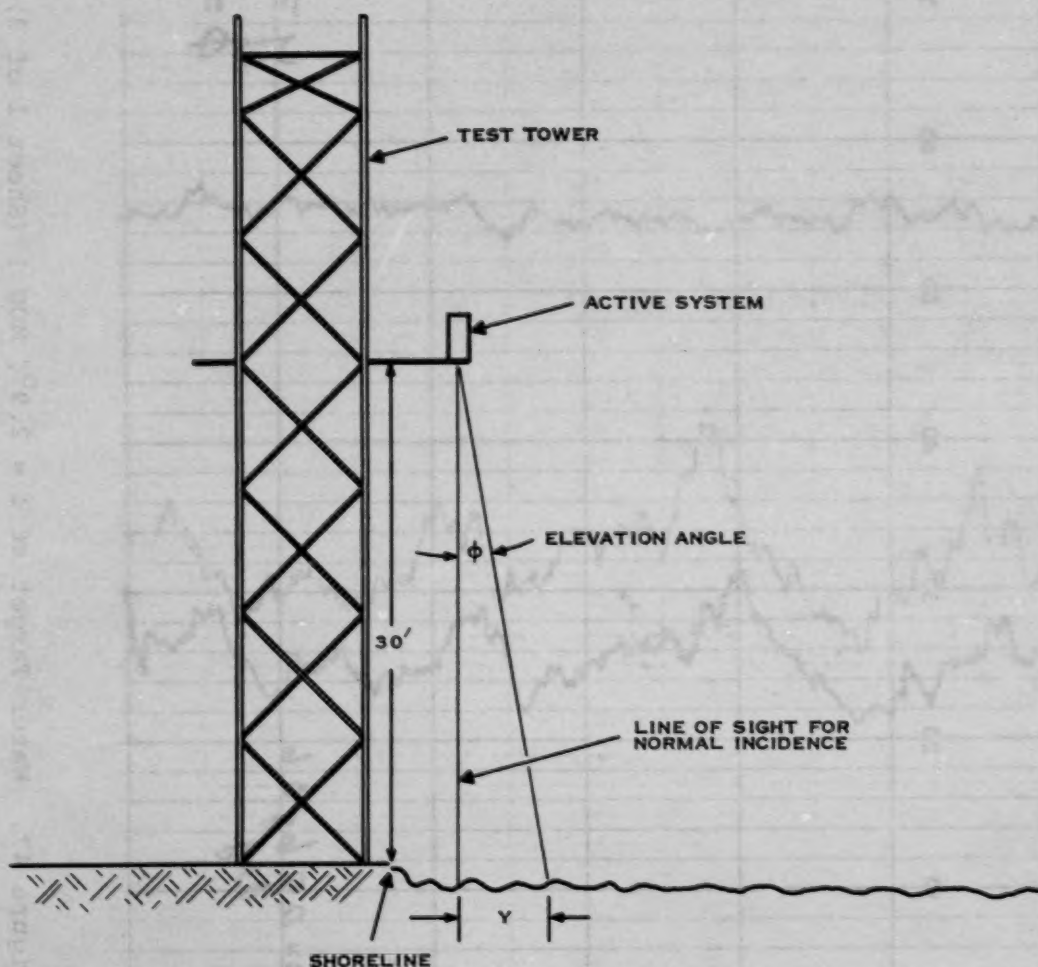


Figure 46. Geometry of Scan Data at 30 Feet

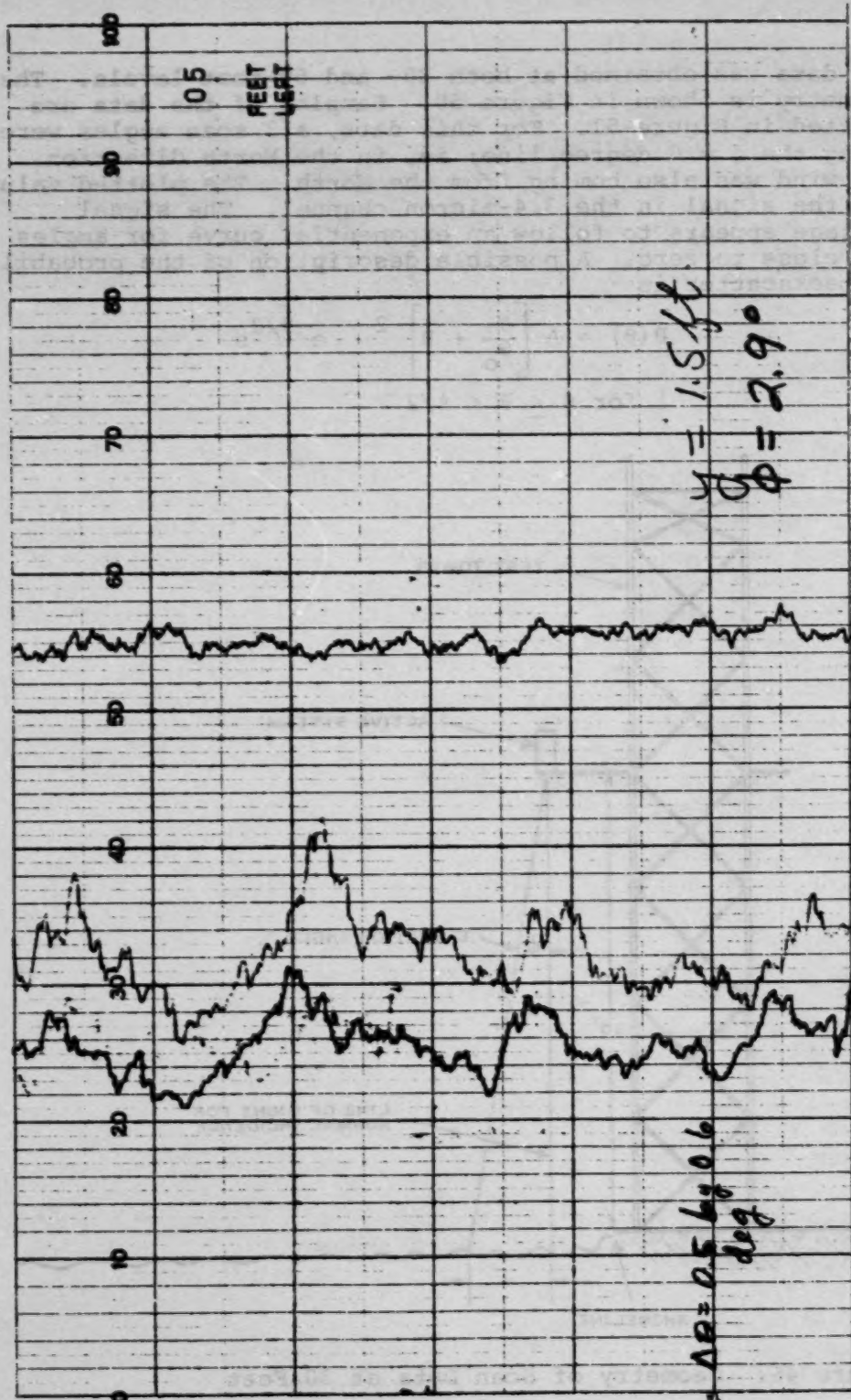


Figure 47. Water Target at $\phi = 2.9^\circ$, MOD 1 (Sheet 1 of 3)

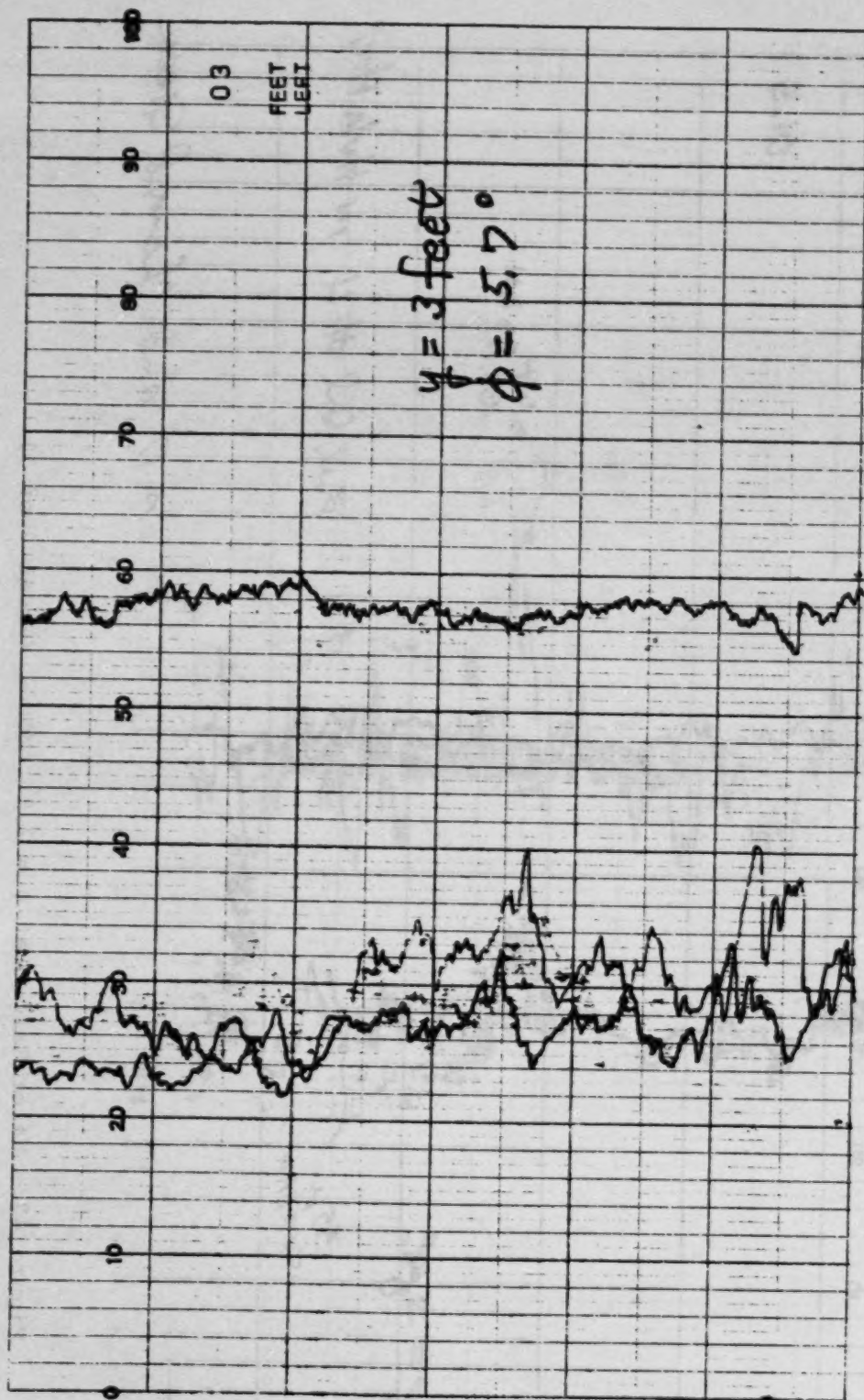


Figure 47. Water Target at $\phi = 2.9^\circ$, MOD 1 (Sheet 2 of 3)

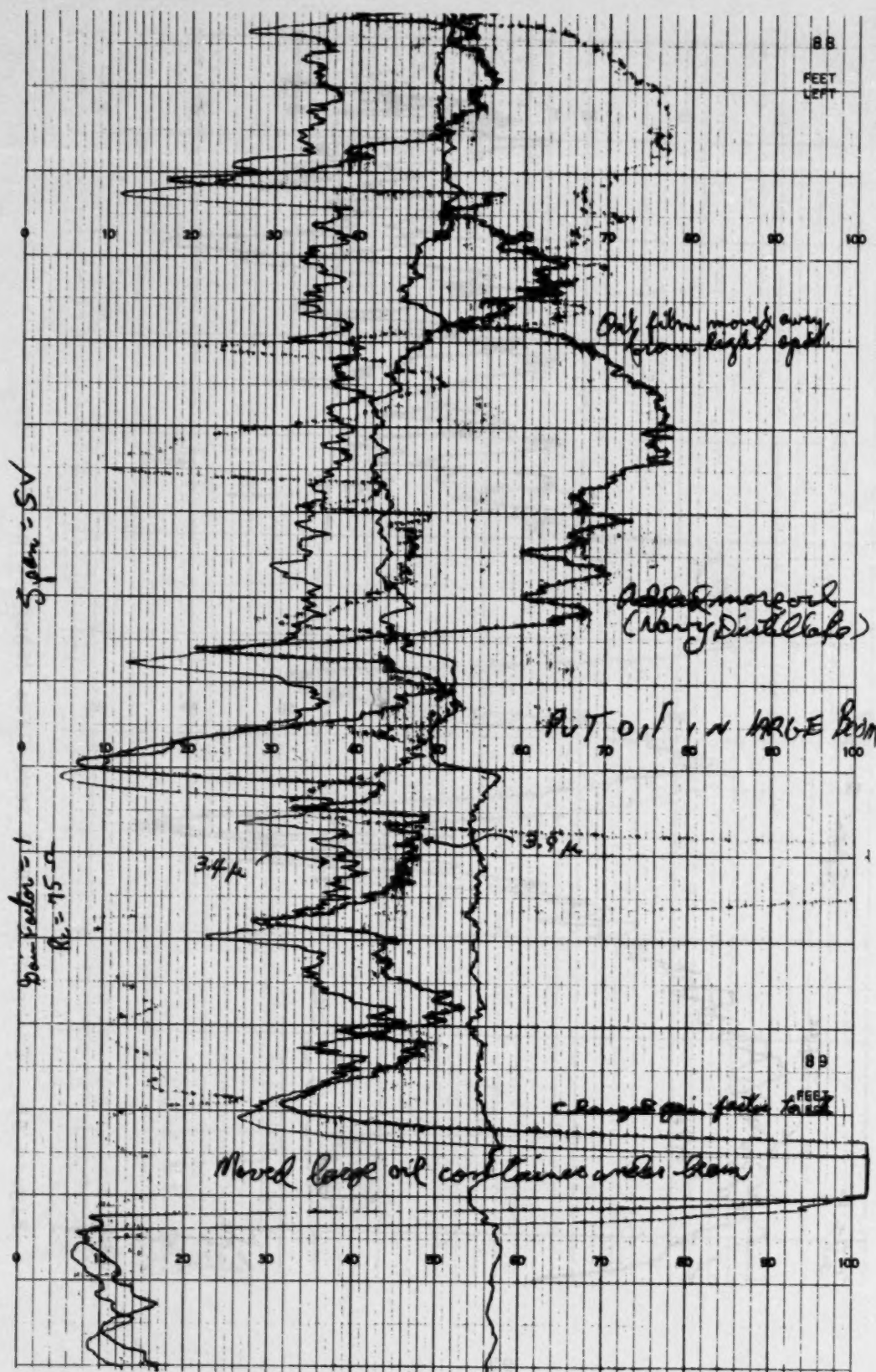


Figure 48. Example of MOD 2 Text Data (Sheet 1 of 2)

Figure 48. Example of MOD 2 Text Data (Sheet 2 of 2)

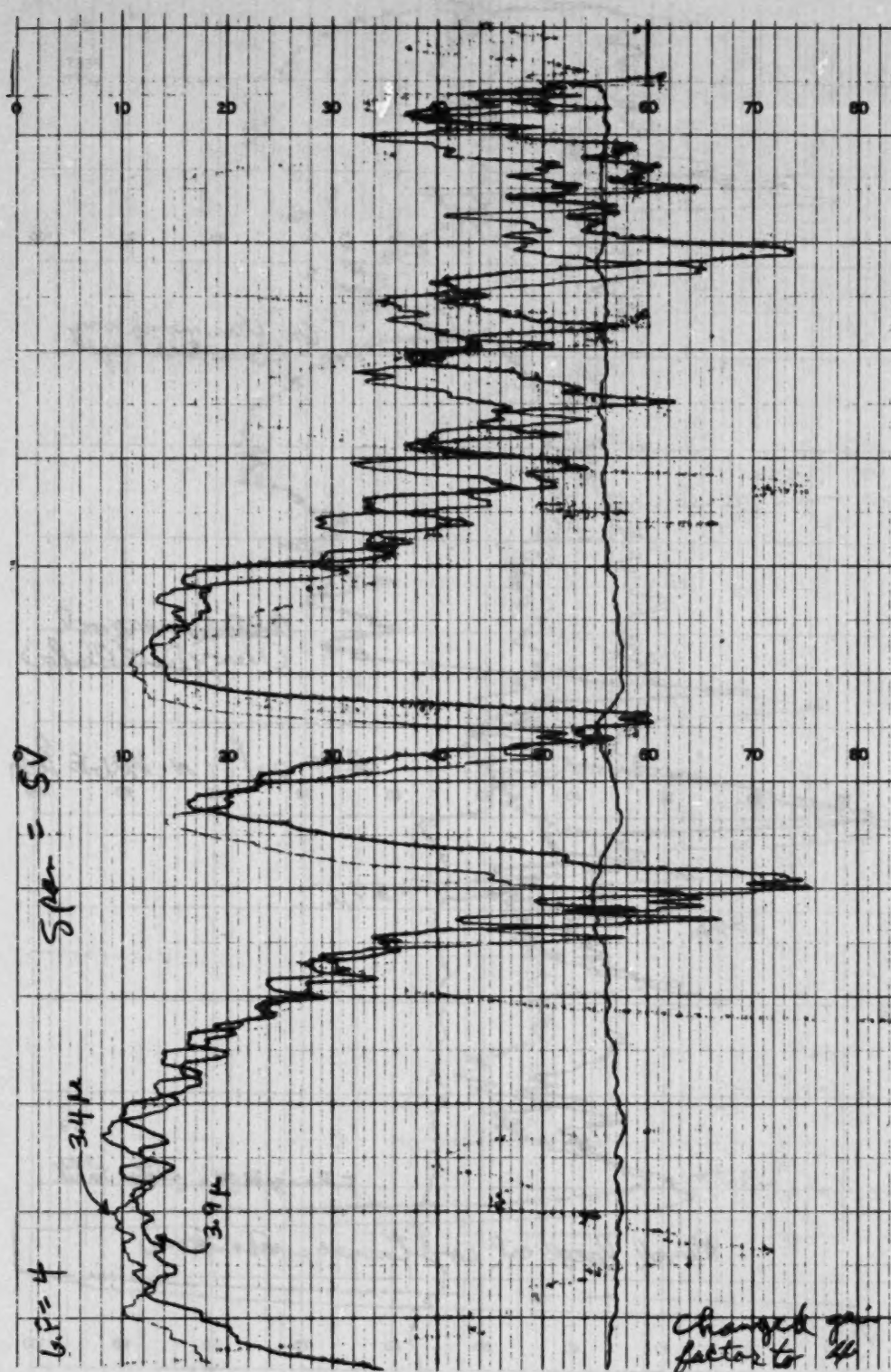


Figure 48. Example of MOD 2 Text Data (Sheet 2 of 2)

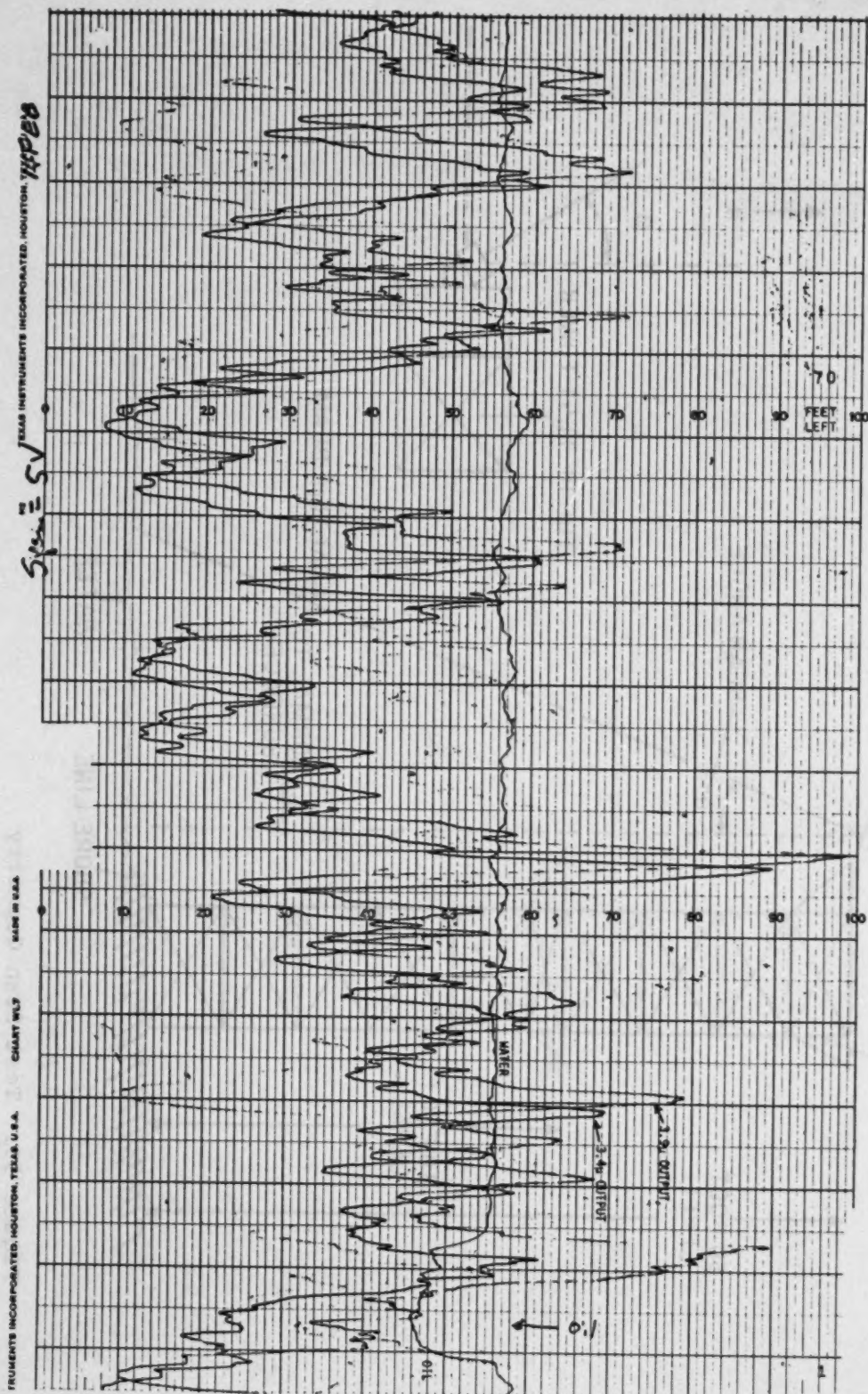


Figure 49. Example of Water and Oil Discrimination

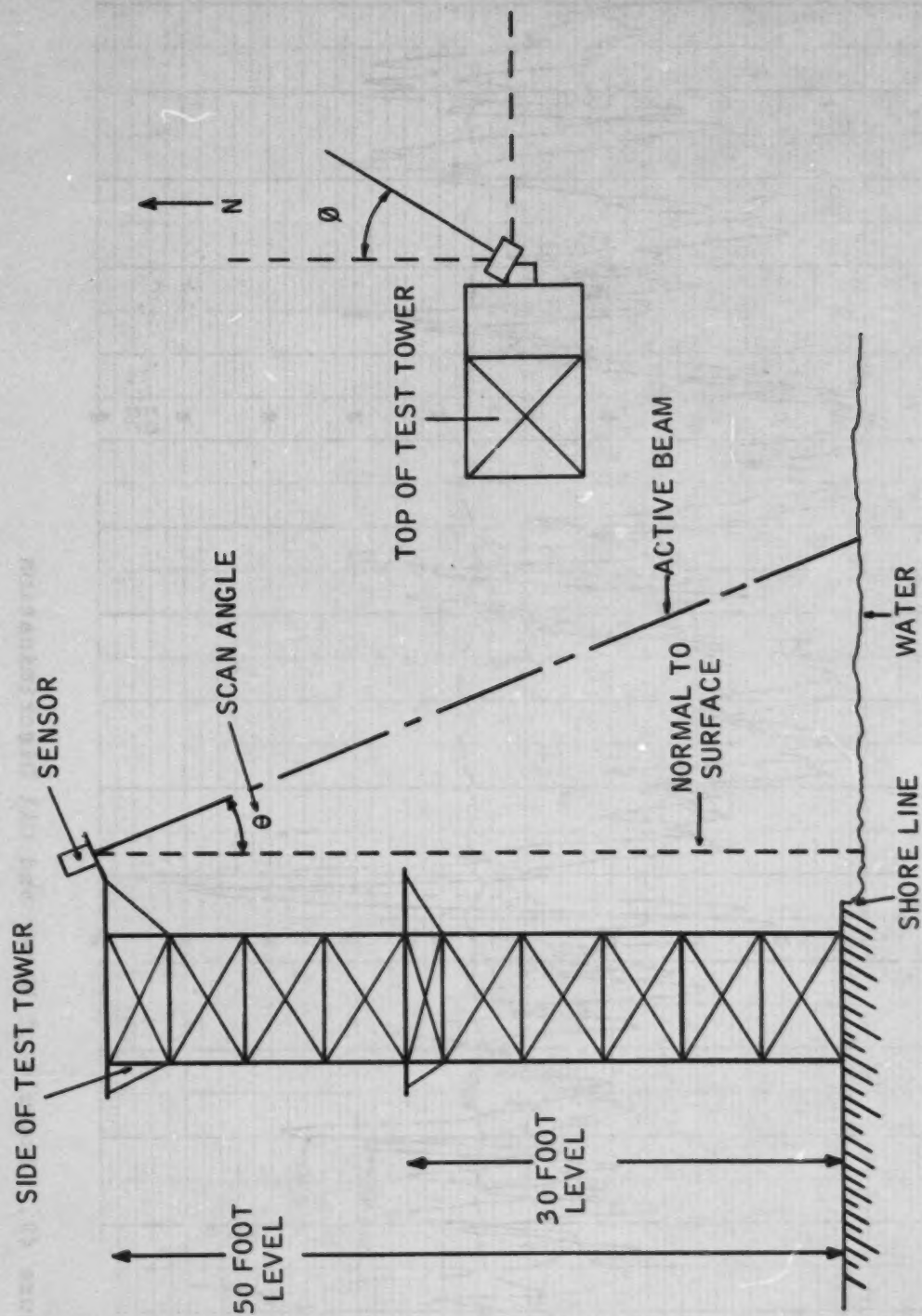


Figure 50. Test Scan Geometry

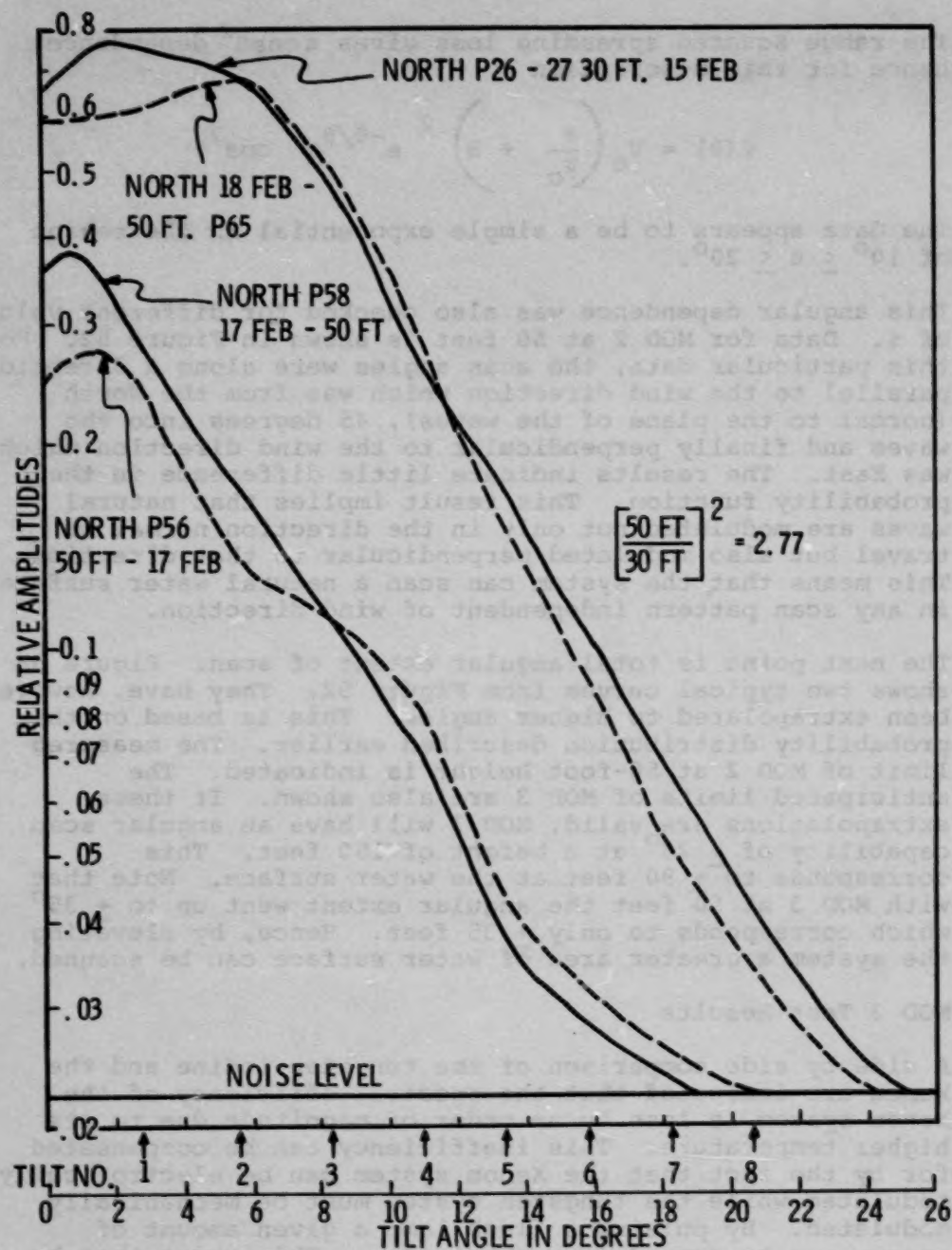


Figure 51. MOD 2 Signal Amplitude Versus Scan Angle for 30- and 50-Foot Heights

The range squared spreading loss gives a $\cos^2 \theta$ dependence, hence for this description

$$V(\theta) = V_0 \left(\frac{\theta}{\theta_0} + B \right)^2 e^{-\theta/\theta_0} \cos^2 \theta$$

The data appears to be a simple exponential in the region of $10^\circ \leq \theta \leq 20^\circ$.

This angular dependence was also checked for different values of ϕ . Data for MOD 2 at 50 feet is shown in Figure 52. For this particular data, the scan angles were along a direction parallel to the wind direction which was from the North (normal to the plane of the waves), 45 degrees into the waves and finally perpendicular to the wind direction which was East. The results indicate little difference in the probability function. This result implies that natural waves are modulated not only in the direction normal to travel but also modulated perpendicular to that direction. This means that the system can scan a natural water surface in any scan pattern independent of wind direction.

The next point is total angular extent of scan. Figure 53 shows two typical curves from Figure 52. They have, however, been extrapolated to higher angles. This is based on the probability distribution described earlier. The measured limit of MOD 2 at 50-foot height is indicated. The anticipated limits of MOD 3 are also shown. If these extrapolations are valid, MOD 3 will have an angular scan capability of $\pm 28^\circ$ at a height of 150 feet. This corresponds to ± 90 feet at the water surface. Note that with MOD 3 at 50 feet the angular extent went up to $\pm 35^\circ$ which corresponds to only ± 35 feet. Hence, by elevating the system a greater area of water surface can be scanned.

MOD 3 Test Results

A side by side comparison of the tungsten-iodine and the Xenon arc indicated that the spectral efficiency of the Xenon system is less by an order of magnitude due to its higher temperature. This inefficiency can be compensated for by the fact that the Xenon system can be electronically modulated while the tungsten system must be mechanically modulated. By pulsing a flash lamp a given amount of energy can be dumped in a short time. This means that by pulsing, a relatively low wattage CW lamp can produce high peak wattage signals. Even though the Xenon system is spectrally inefficient, it can produce a factor of 10

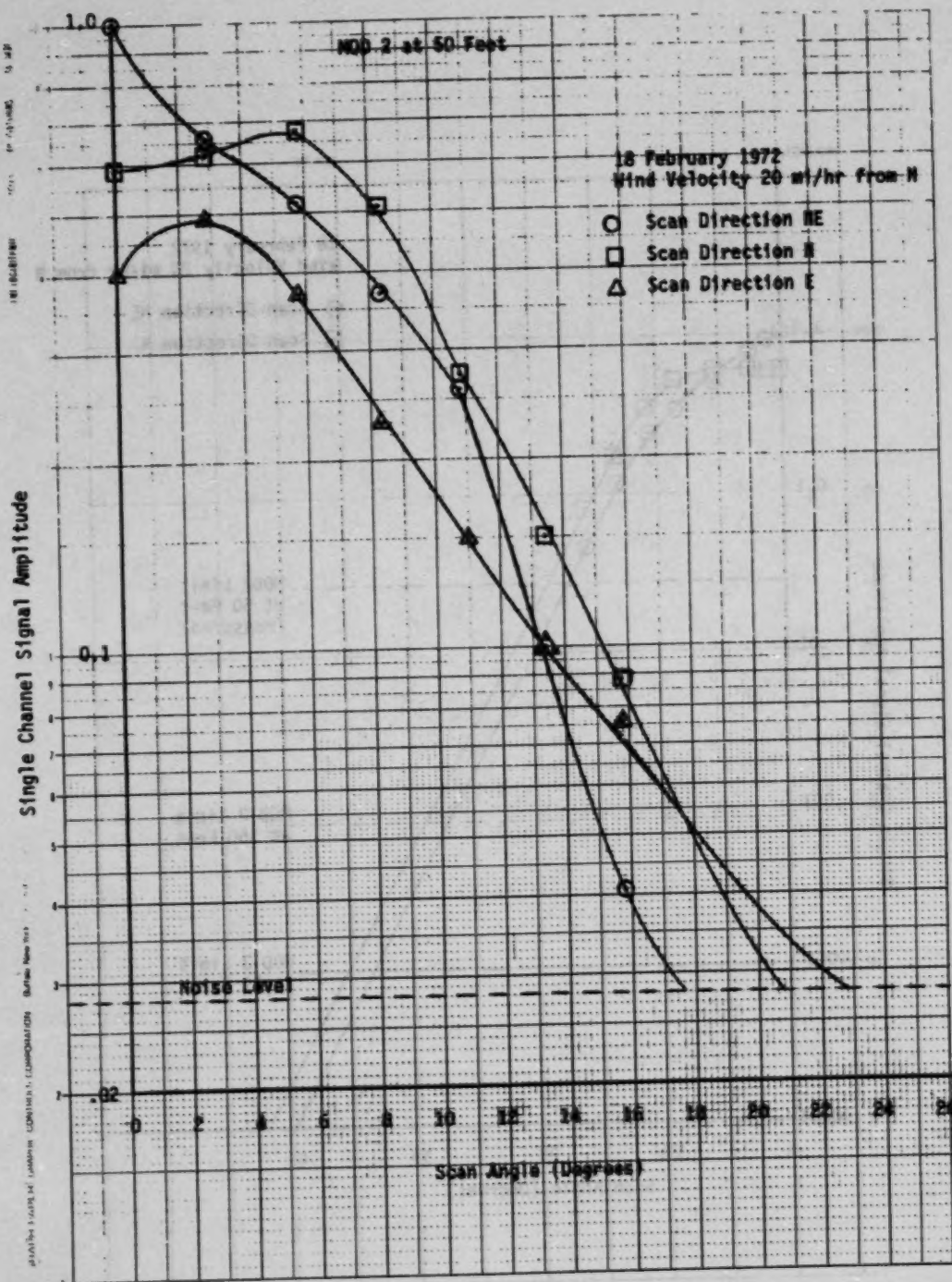


Figure 52. MOD 2 Signal Amplitude Versus Angle for Three Scan Directions

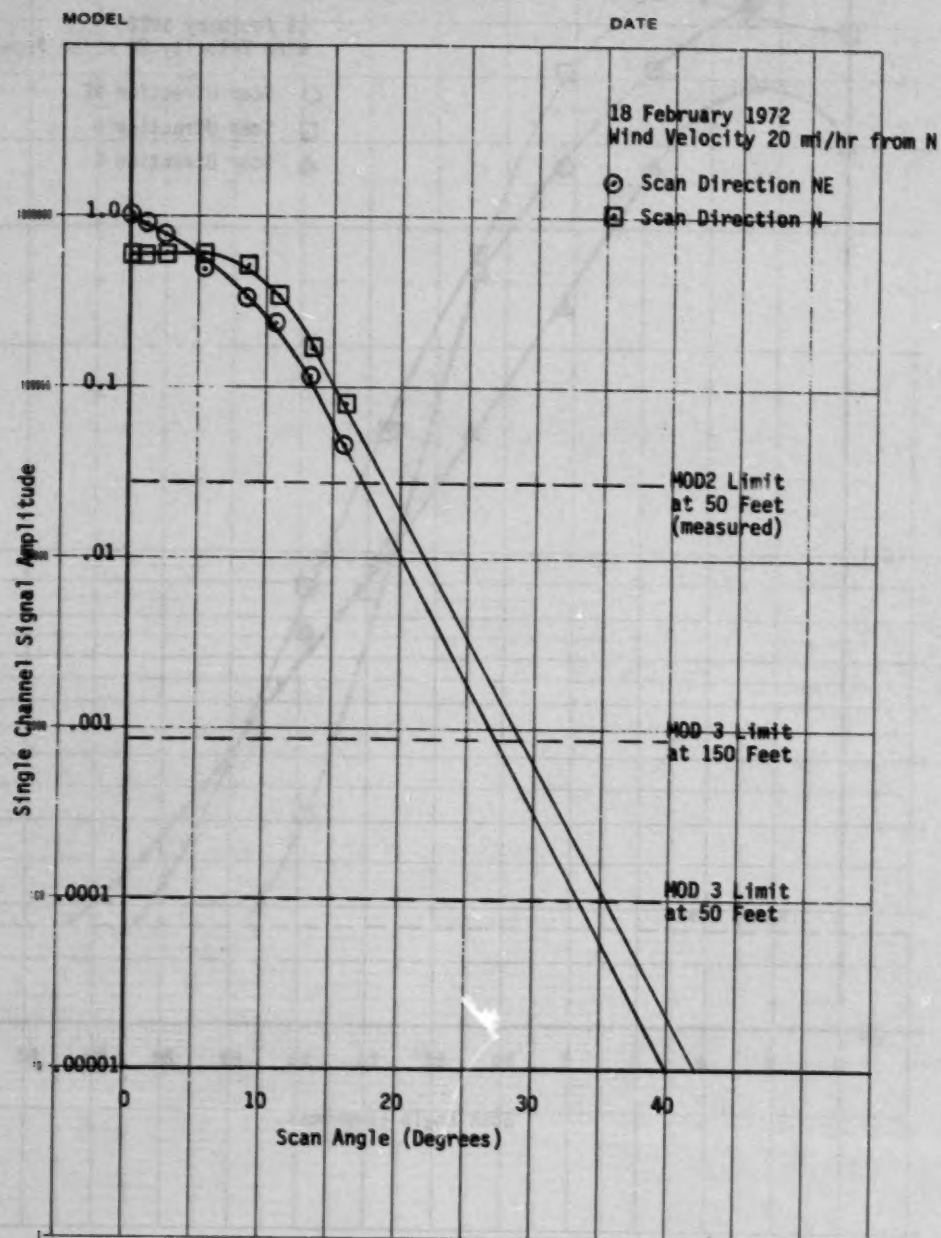


Figure 53. Angular Scan Limits of MODs 2 and 3

increase in system range over a system using tungsten-iodine lamp. Because of certain advantages unique to each system, it was decided to build a unit which would accept either light source with a few minor modifications to effect the interchange. The system which used a tungsten lamp is designated as MOD 2 and the Xenon arc system is called MOD 3. It consists of the Xenon lamp, a parabolic reflector, the optic plate, a 20 joule capacitor bank and a short arc lamp pulser. In addition, four printed circuit cards which are compatible with system wiring are required.

In the MOD 3 setup, the interference at the output caused by the high voltage firing pulse for the Xenon lamp and, thus, the noise level at the output, was reduced to an insignificant value by shielding the high voltage line and its ground return between the pulser and the lamp, and by gating the 75 microsecond detected pulse for 25 microseconds centered around the peak. It was also determined that for a 75 microsecond pulse 20 joules of energy would give complete ionization of the gas and thus give a more stable color temperature than lower energy levels. This power level is compatible with the 10^6 pulses per lamp curve discussed in Section V.

The system was tested in the laboratory and was demonstrated to distinguish between water and oil. The data shown in Figure 55 is not quantitative since a projection distance of only 10 feet was available whereas the system was designed for 300 feet. Techniques used to attenuate the beam by a factor of 1000 produced some distortion and extraneous reflections. However, the data does show a clear distinction between oil and water.

Since MOD 1, 2 and 3 had been successfully demonstrated to distinguish between oil and water in the laboratory, the MOD 1 and 2 had also been demonstrated at 30 and 50 feet on a stock pond which periodically had wave action up to 3 or more inches high, the next step was to field test the sensor at a height and in an environment similar to final system application. Since the system concept of oil versus water discrimination had been established as valid so long as signal was present, the only remaining factor was signal level versus environment. The presence of oil was not necessary for these tests; thus, a site 91 feet above the Gulf of Mexico was chosen.

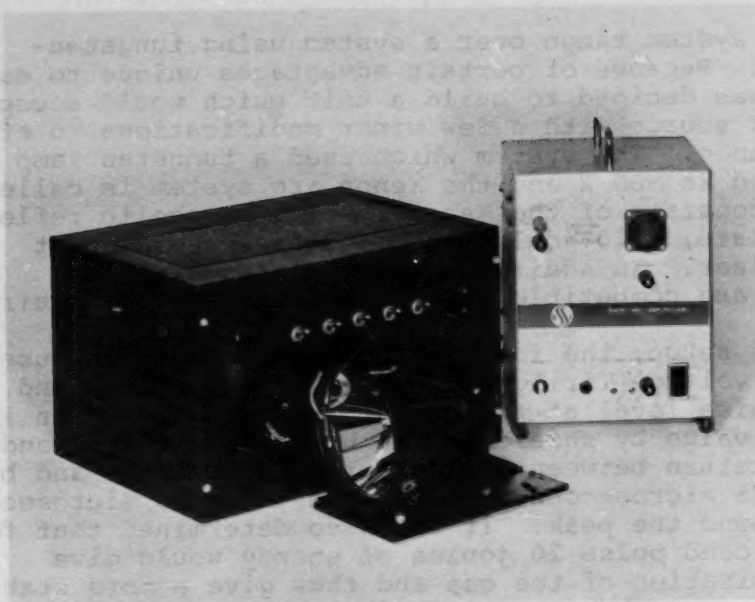


Figure 54. Modification Kit for MOD 3

This test site was located on the seventh floor terrace of the Flagship Hotel in Galveston, Texas. The hotel is built on a wharf extending 100 yards into the Gulf of Mexico and the seventh floor is approximately 91 feet above the surface of the water during normal tide. The test set up for MOD 3 is shown in Figure 56. MOD 3 was operated during the first two days while moderate waves (6 to 12 inches) were present. Figure 56 also shows typical waves that were present during those two days.

Test performed show that the system has reserve capabilities which would permit operation at a 300 foot height at a large tilt angle. The system was checked at 9 degrees and 14 degrees and strong signal returns were measured during this period of moderate waves. However, some problems were experienced with the electronic circuitry, which prevented the collection of stable data out of the log difference amplifier. Typical data is shown in Figure 57. The gains setting of the pulse amplifiers were reduced by a factor of 10 to prevent saturation; thus, this factor of 10 would allow operation at 300 feet. The chart recorder spans were

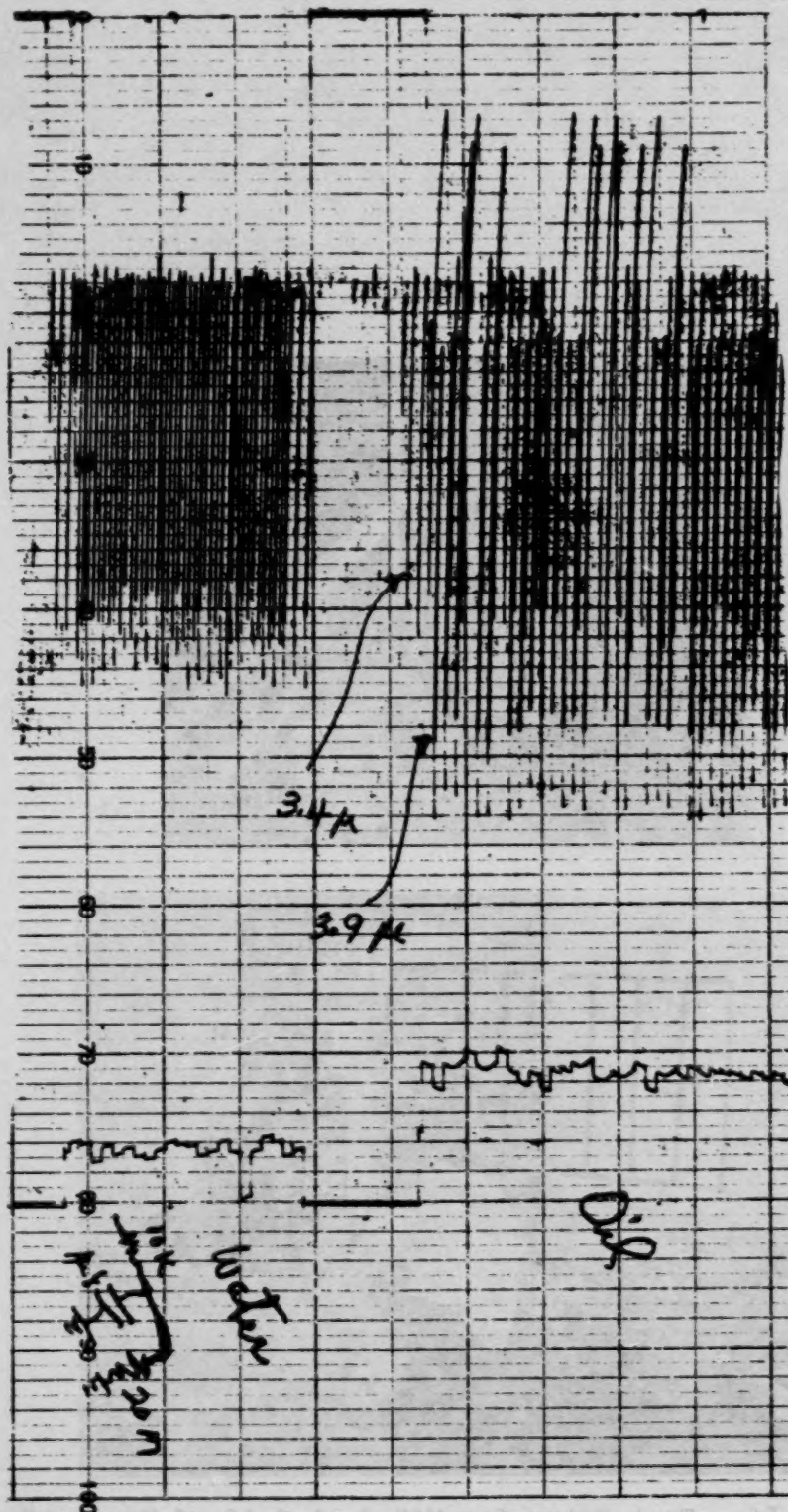


Figure 55. MOD 3 Lab Data

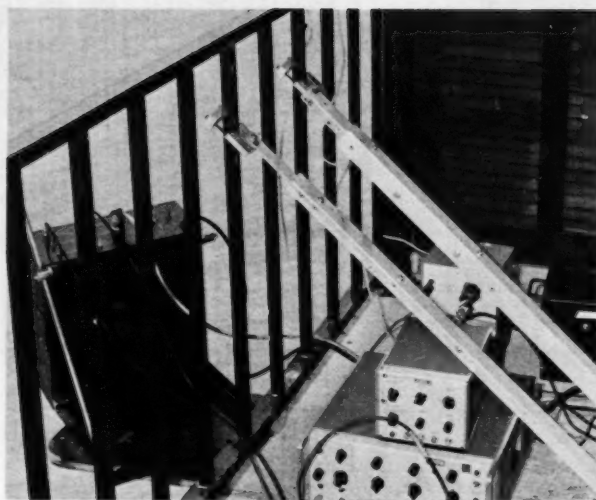


Figure 56. Test Setup for MOD 3 at Gulf of Mexico Test Site

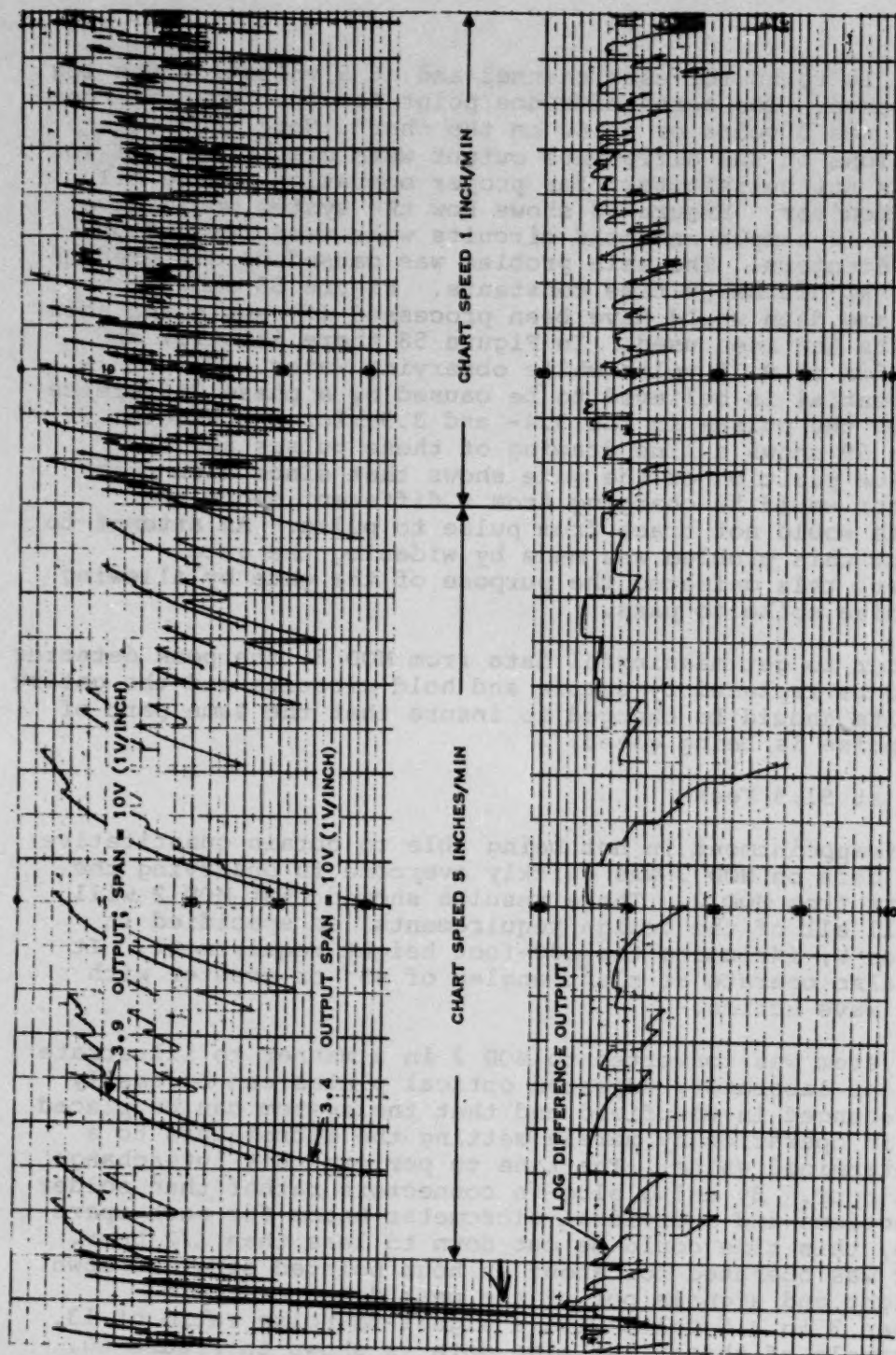


Figure 57. Typical Data from MOD 3 at 91 Feet

A

set at 10 volts for each channel and at 5 volts for the log difference. The zero reference point for the log difference output was 3 volts or at 60 on the chart. Note that the excursions on the difference output were greater than 1 volt. This is not satisfactory for proper operation of the oil spill monitor. Figure 58 shows how the system would have reacted if sample and hold circuits were used instead of peak detectors. The main problem was caused by differences in the RC discharge time constants. Figure 58 shows how this same data would have been processed if sample and hold circuits had been used. In Figure 58 there is still an excursion of 0.35 volts while observing water. This differential is believed to be caused by a phase difference between the pulses in the 3.4- and 3.9-micron channels. Figure 59 shows a line drawing of these pulses and the relative position of the gate shows that since each peak detector would be charging from a different slope the outputs would not trace from pulse to pulse. An attempt to correct this problem was made by widening the gate. However, this defeated the purpose of the gate by allowing the noise spike to pass.

In order to get meaningful data from MOD 3, the peak detector should be replaced by sample and hold circuits and the gating circuits should be changed to insure that the same part of each pulse is being gated.

MOD 2 at 91.5 Feet

The disappointment in not being able to obtain quantitative field data on MOD 3 was quickly overcome in observing the results from MOD 2. These results showed that MOD 2 will fulfill all of the design requirements, as specified in Section V, including the 300-foot height requirement. It will also operate at slant angles of 45° or greater with heavy wave action.

The system was converted to MOD 2 in a manner to illustrate that the laboratory adjusted optical plates can be easily interchanged in the field and that the system can be placed back in operation by merely setting the micrometers to a predetermined value. The time to perform this interchange was 1 hour. By using plug-in connectors rather than solder connections and individual micrometer heads for each spare plate, this time could be cut down to less than 1/2 hour. MOD 2 was operated for about an hour pointed straight down at night and signals out of the peak detectors were between 3 to 3.5 volts with a signal-to-noise ratio of 13. An example of this night time data is shown in Figure 60.

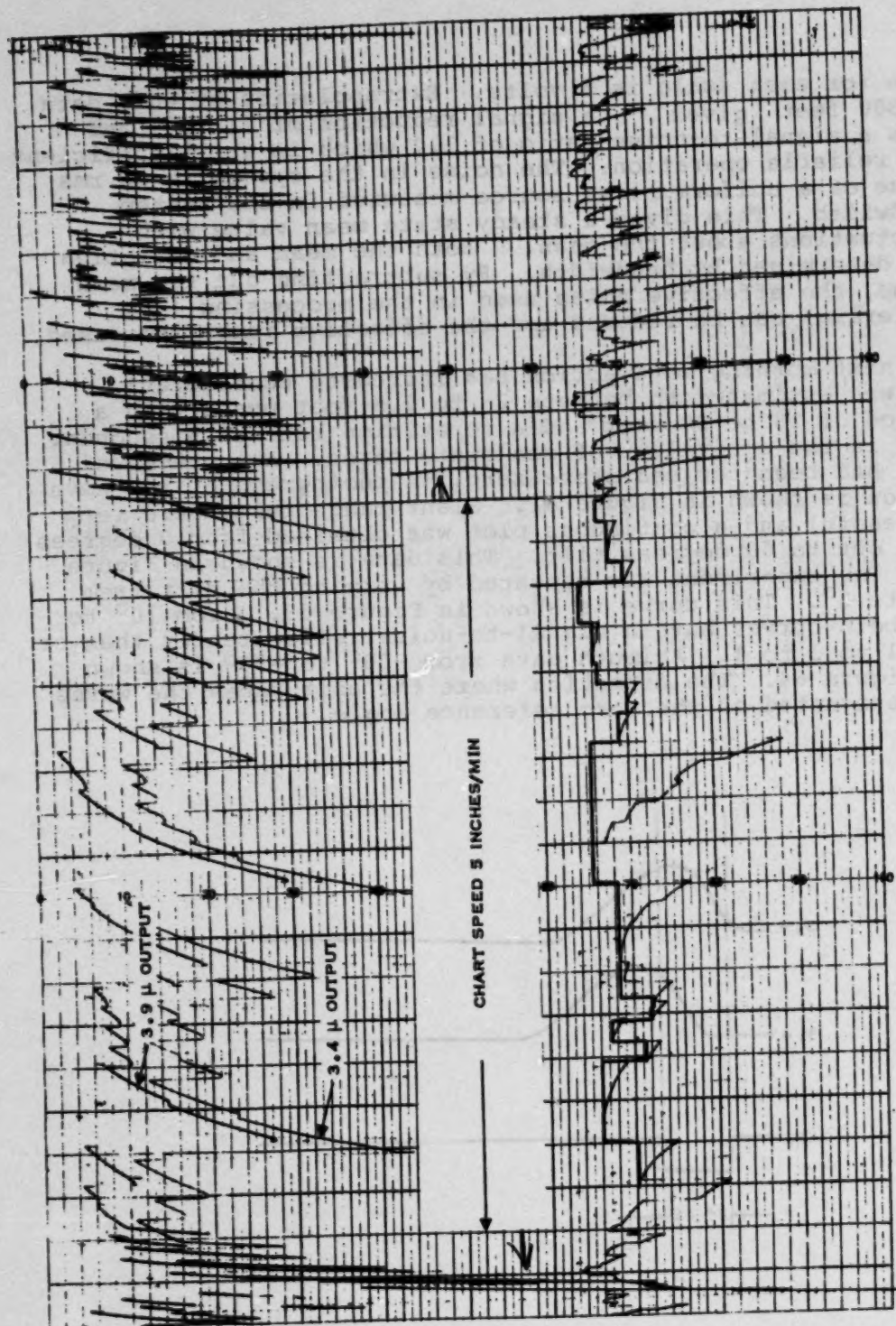


Figure 58. Predicted Operation with Sample and Hold Circuits

Span for each scale is 5 volts. Extrapolation of this data to 300 feet gives a signal reduction of 11 to 1 and thus a signal-to-noise ratio of 1.2 which is still sufficient for reliable operation. The noise in the system is an rms value of a uniform noise source measured in the system bandwidth. This gives a steady state mean value with fluctuations about the mean. Both the mean and deviation are determined by bandwidth. By subtracting out the mean value, the effective noise used in the processing (log differing) can be reduced and the effective range increased.

The next morning wave action had increased considerably and was estimated to be between 2- to 2.5-foot peaks with a period of 15 to 20 feet and a repetition rate of 5 seconds. This is the equivalent of sea state three. All previous data had been for sea state zero. A photograph of the wave action is shown in Figure 61. Slant range tests were very successful and a continuous plot was obtained from 0 degrees tilt out to 60 degrees tilt. This data is shown in Figure 62. The experiment was repeated by varying the tilt from 60° to 0° . This curve is shown in Figure 63. From 10° to 40° both curves have a signal-to-noise ratio greater than or equal to 3 to 1. Azimuth data from -30° to $+90^\circ$ is shown in Figure 64. The direction where the unit faces the waves is designated as the zero reference angle.

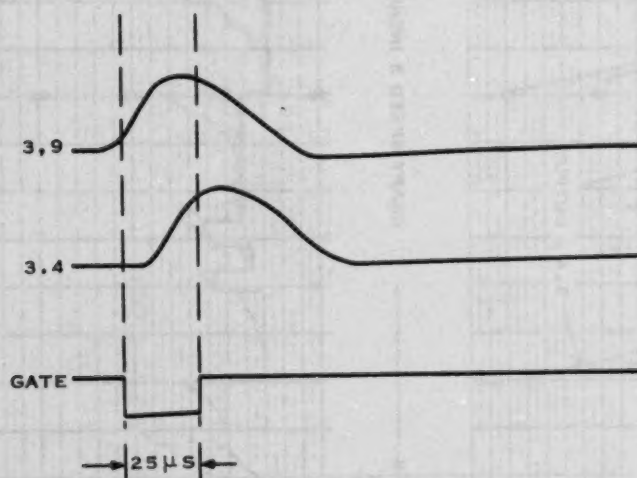


Figure 59. Pulse Sampling

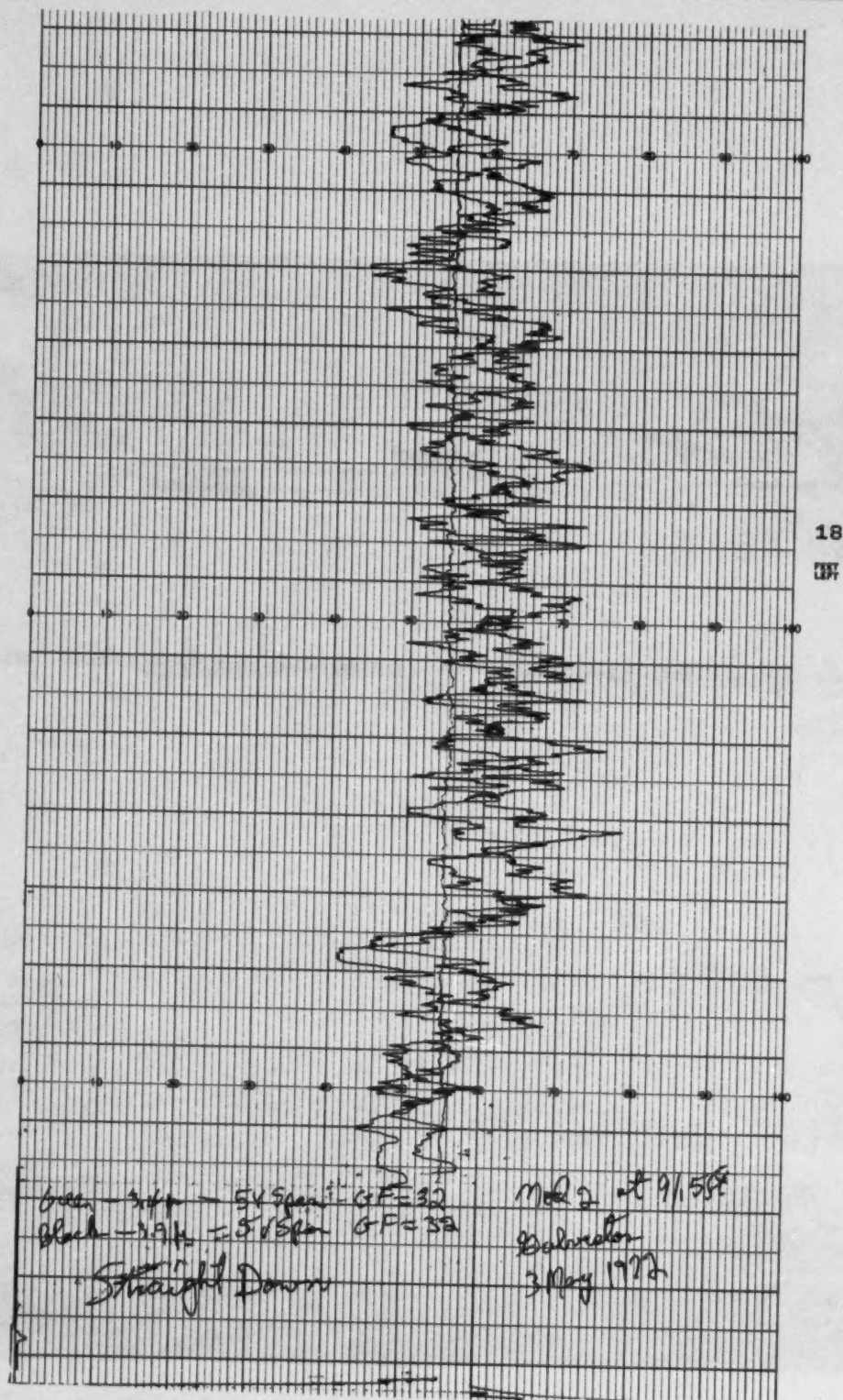


Figure 60. Nighttime Data from MOD 2 at 91 Feet

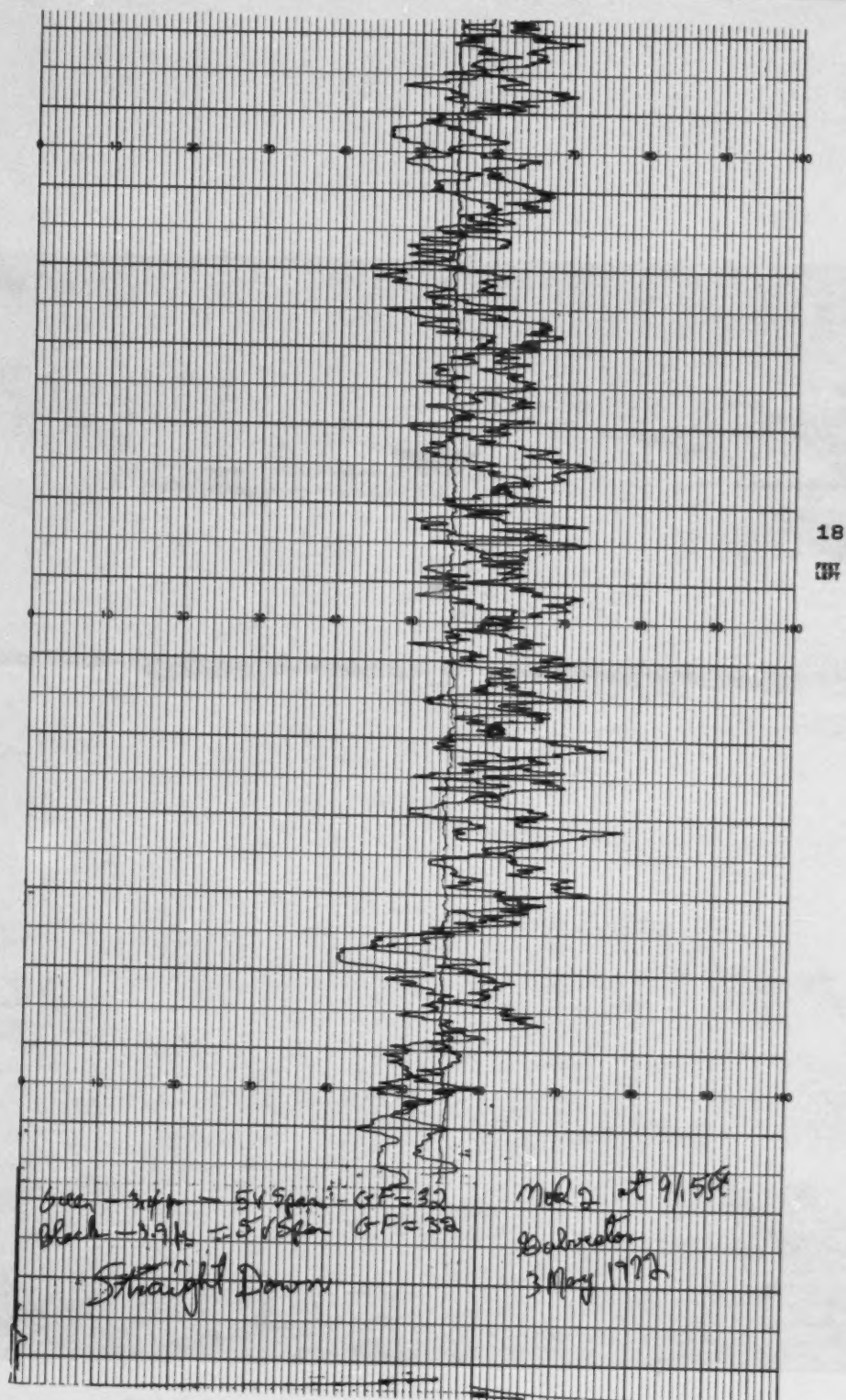


Figure 60. Nighttime Data from MOD 2 at 91 Feet



Figure 61. Photograph of Wave Action

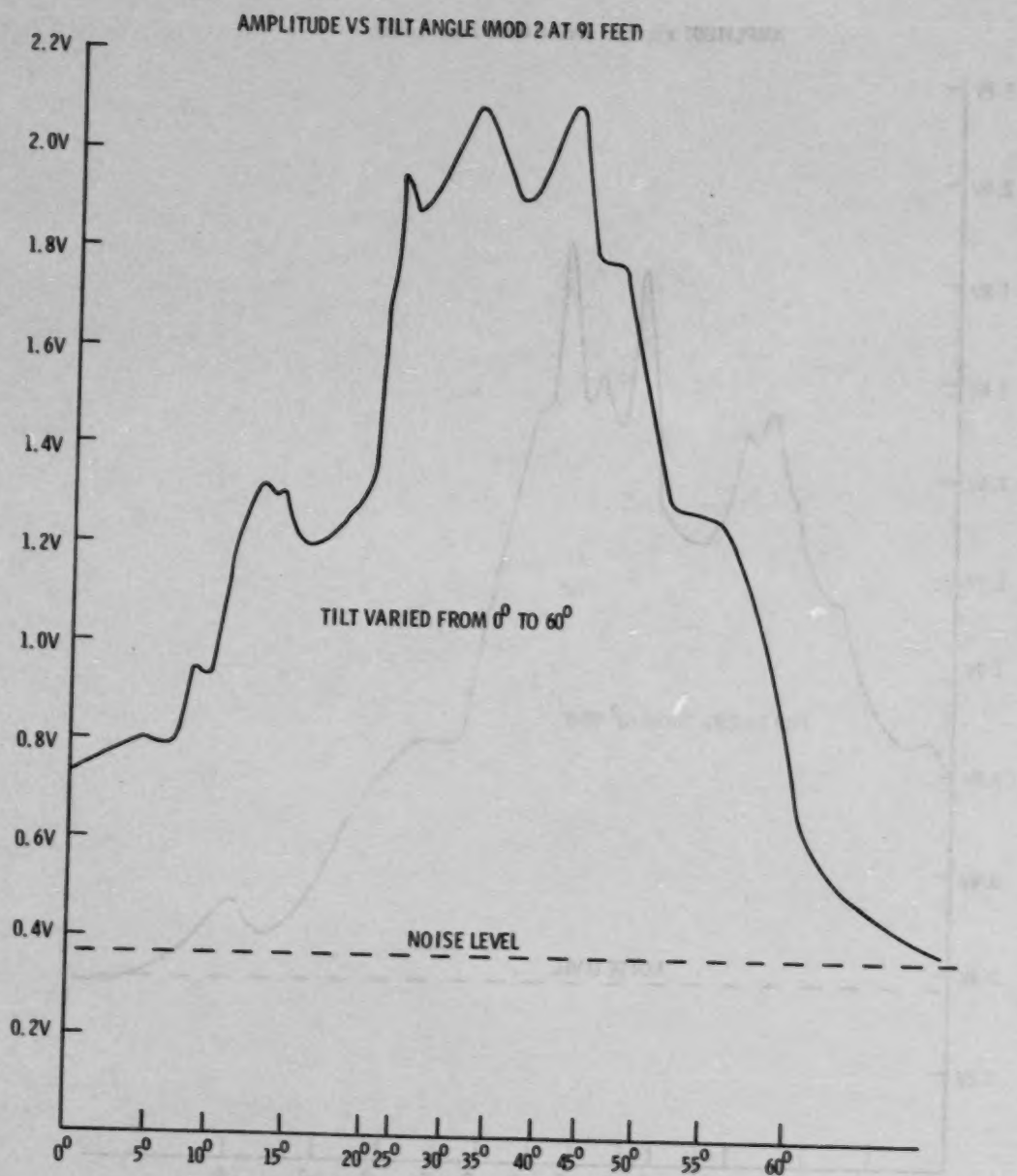


Figure 62. Amplitude Versus Tilt Angle for MOD 2 at 91 Feet
Angle 0° to 60°

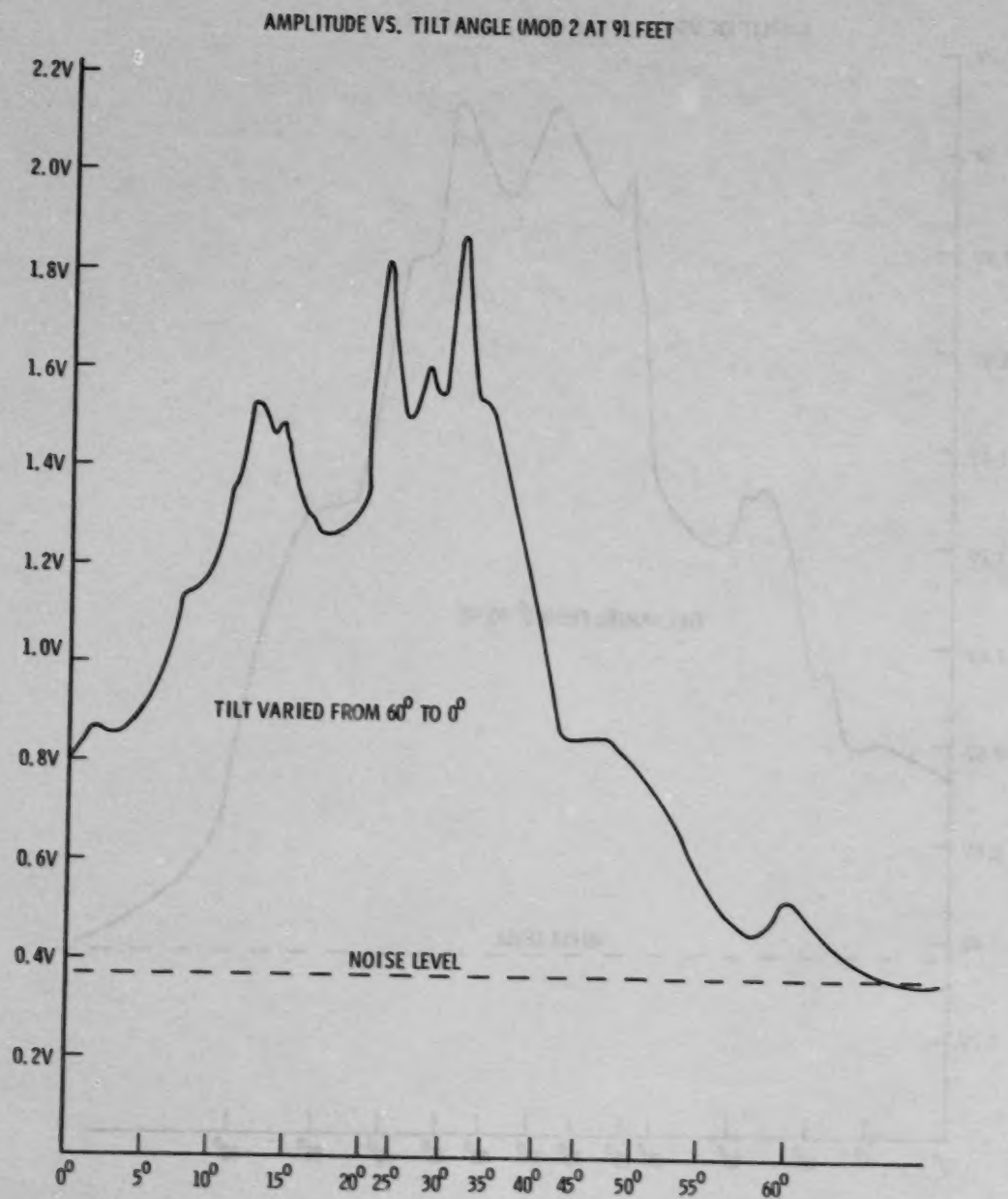


Figure 63. Amplitude Versus Tilt Angle for MOD 2 at 91 Feet
Tilt Angle 60° to 0°

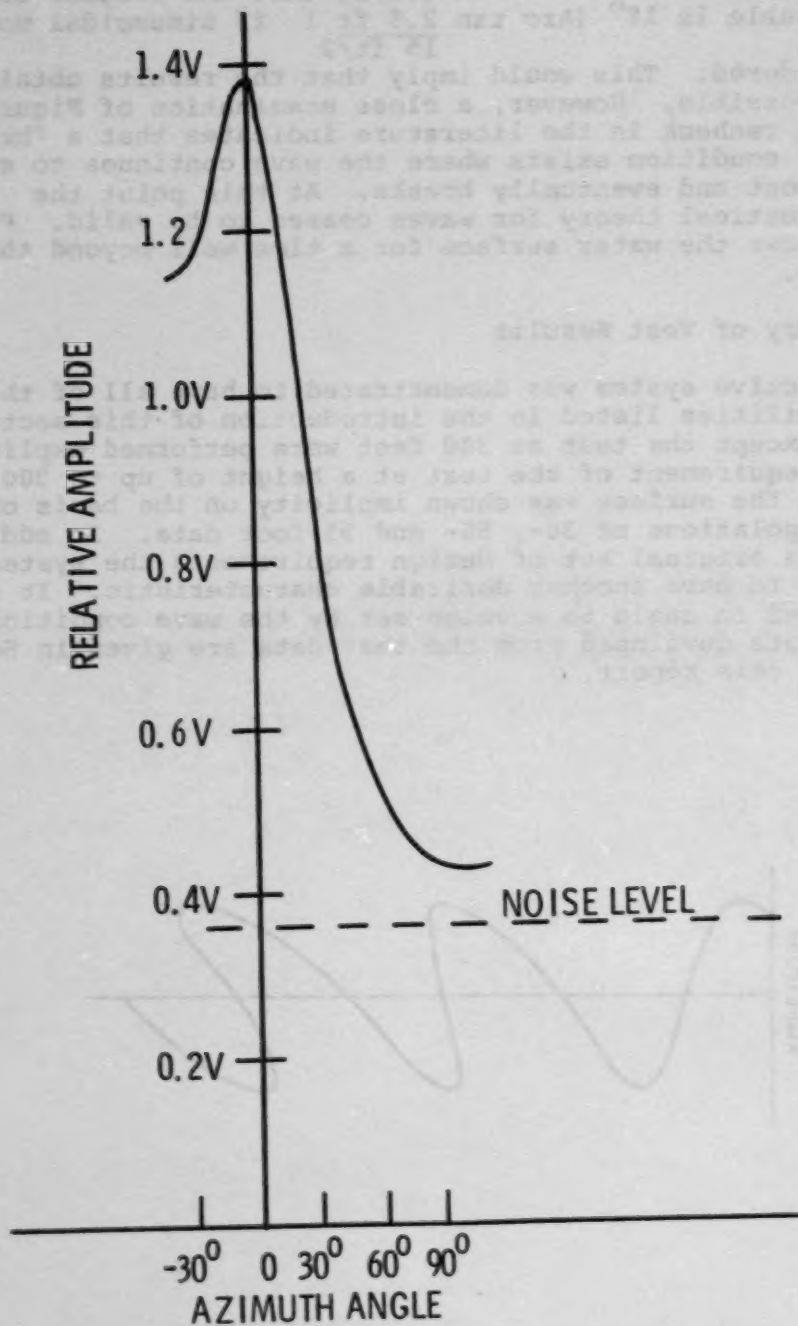


Figure 64. Amplitude Versus Azimuth Angle, Tilt Angle 36°

An analysis of the wave action present at the time that the tilt data was recorded indicates that the largest slope available is 18° (Arc tan $\frac{2.5 \text{ ft}}{15 \text{ ft}/2}$) if sinusoidal motion is

considered. This would imply that the results obtained were not possible. However, a close examination of Figure 61 and a recheck in the literature indicates that a "break wave" condition exists where the wave continues to steepen in front and eventually breaks. At this point the mathematical theory for waves ceases to be valid. Figure 65 shows the water surface for a time well beyond the breaking point.

Summary of Test Results

The active system was demonstrated to have all of the capabilities listed in the introduction of this section. All except the test at 300 feet were performed explicitly. The requirement of the test at a height of up to 300 feet above the surface was shown implicitly on the basis of extrapolations of 30-, 50- and 91-foot data. In addition to the original set of design requirements the system was known to have another desirable characteristic. It can be scanned in angle to a value set by the wave condition. The concepts developed from the test data are given in Section IX of this report.

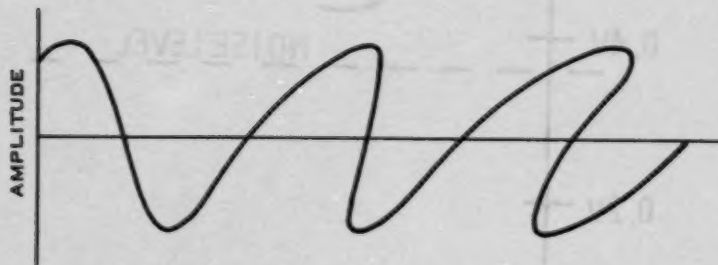


Figure 65. Water Profile After Breaking

SECTION VIII

TEST RESULTS, PASSIVE SENSOR

Oil Type Test

The passive infrared sensor system tested can only detect thermal anomalies. It cannot determine exact oil types by spectroscopy or by any other means used by active systems. With this passive system, various oil types can be deduced by observing the differences in physical characteristics of one oil signature from another. The following paragraphs describe how four oil types were categorized according to their various differing physical characteristics present in their signatures.

Navy distillate was the first sample to be observed. Figure 66 shows the plastic sample ring (3 feet in diameter) with clear water. Figure 67 shows 1/2 ounce of Navy distillate being administered to the ring. Figure 68 shows patches of sheen formed shortly after contact with water. The oil forms a sheen quickly, but does not spread out to cover the entire ring. Figure 69 shows the experimenter stirring the sample for uniformity of sheen over the entire area of the ring. Sheens of oil appear as black, or dark areas, due to the low emission of thin sheens on water. Thick lumps appear as bright spots, indicating higher temperature than water or better emissivity than water.

Figure 70 shows a uniform sheen over the entire area of the ring after stirring. Figure 71 shows the uniform sheen remaining in spite of good wave action.

Diesel fuel oil number 2 was the second sample observed. Figure 72 shows the ring clean again. Figure 73 shows 1/2 ounce of the oil being poured inside of the ring. Figure 74 shows the sample shortly after contact with water. Notice that it has already spread to the entire area of the ring. Figure 75 shows the sheen remaining in spite of the wave action.

Diesel fuel oil number 4 was the third sample observed. Figure 76 shows the ring cleaned out again. Figure 77 shows 1/2 ounce of oil inside the ring. Figure 78 shows the oil spread into patches of sheen, not covering the entire area of the ring. Figure 79 shows the oil spread evenly over the entire area of the ring.

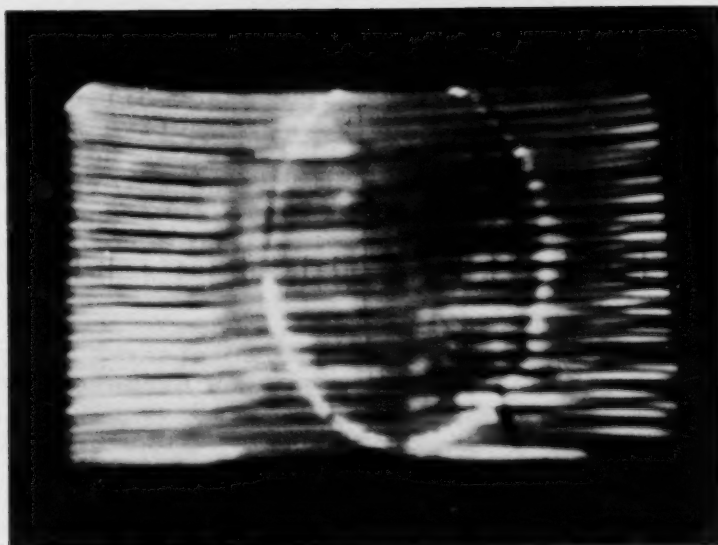


Figure 66. Plastic Ring in Clean Water Before Adding Distillate

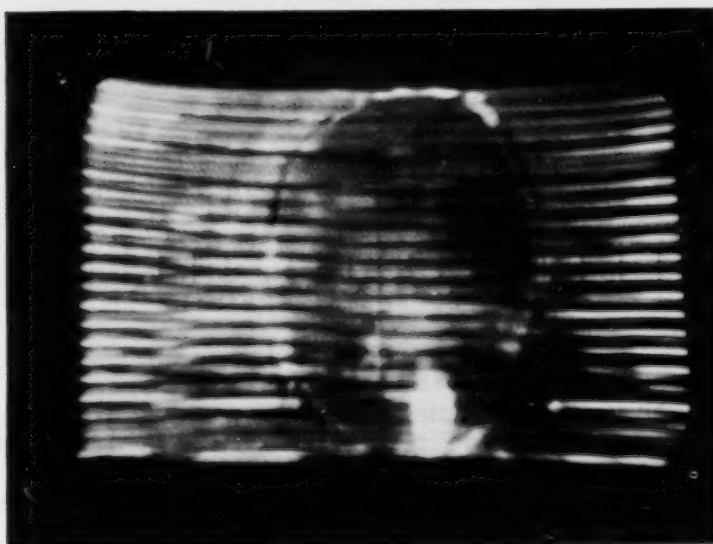


Figure 67. Navy Distillate Being Added to Water Inside Ring

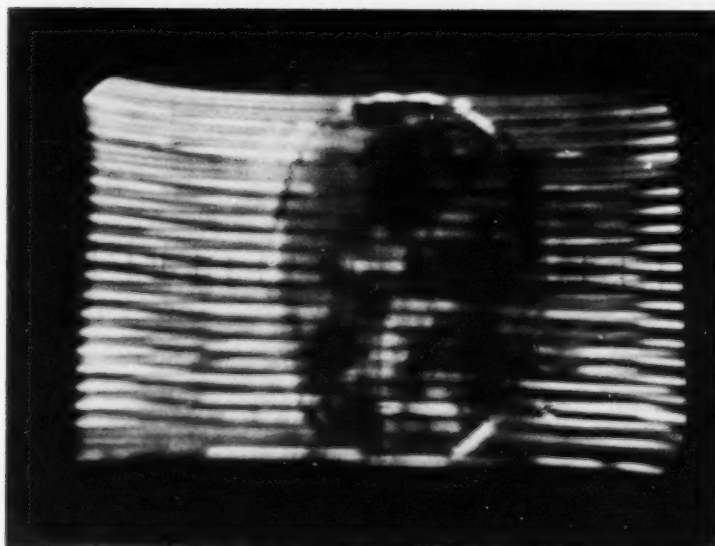


Figure 68. Patches of Distillate Sheen

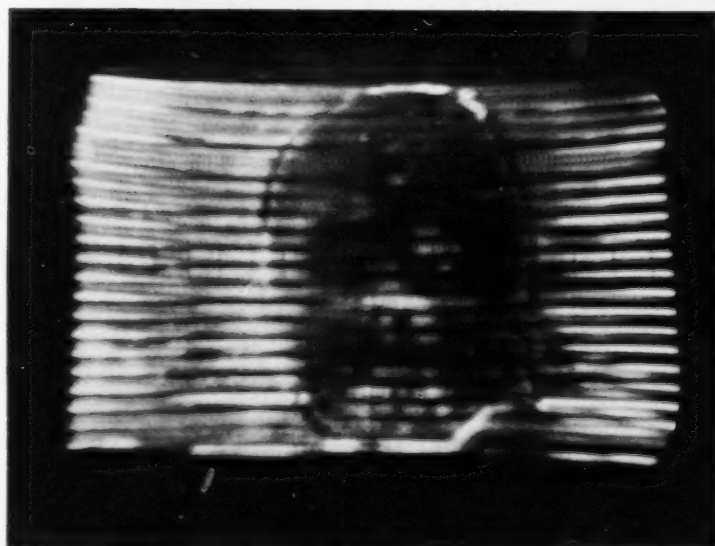


Figure 69. Distillate Being Stirred for Uniformity

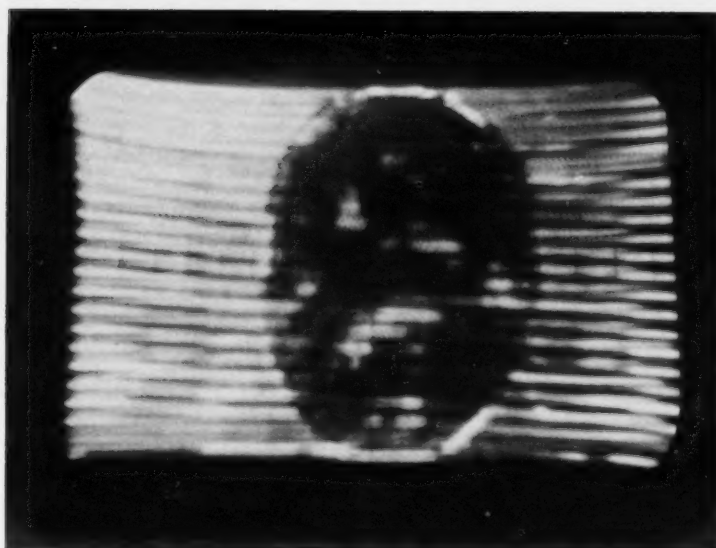


Figure 70. Uniform Distillate Sheen

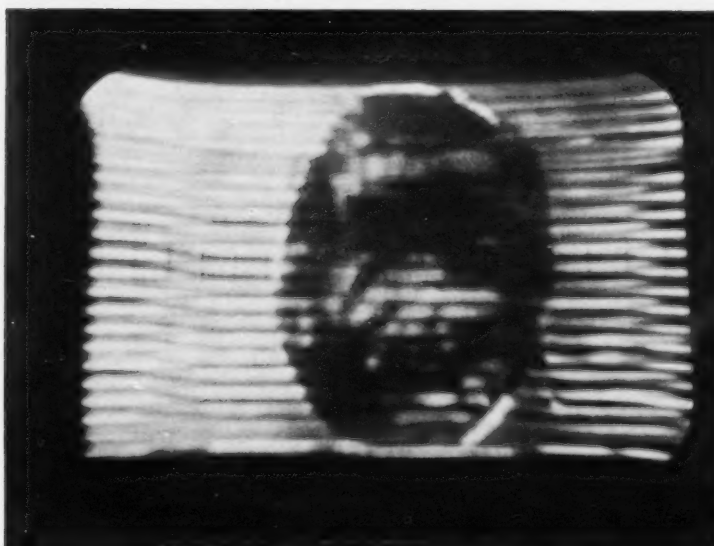


Figure 71. Uniform Distillate Sheen in Presence of Waves

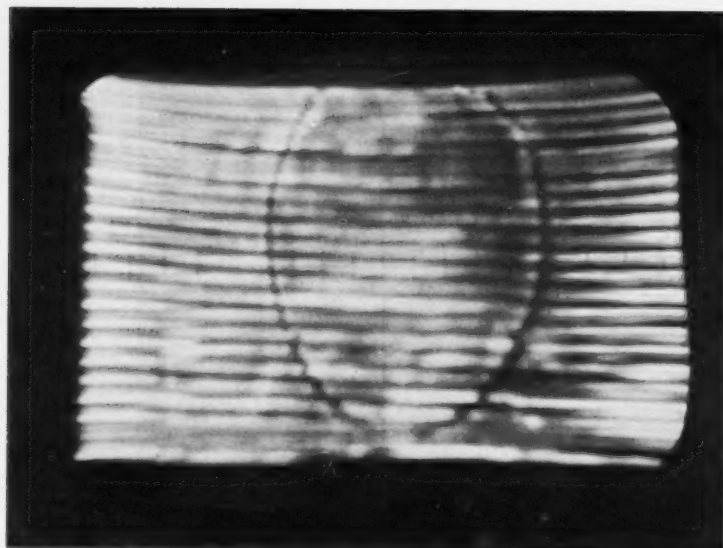


Figure 72. Plastic Ring in Clean Water Before Adding Diesel Fuel Oil No. 2

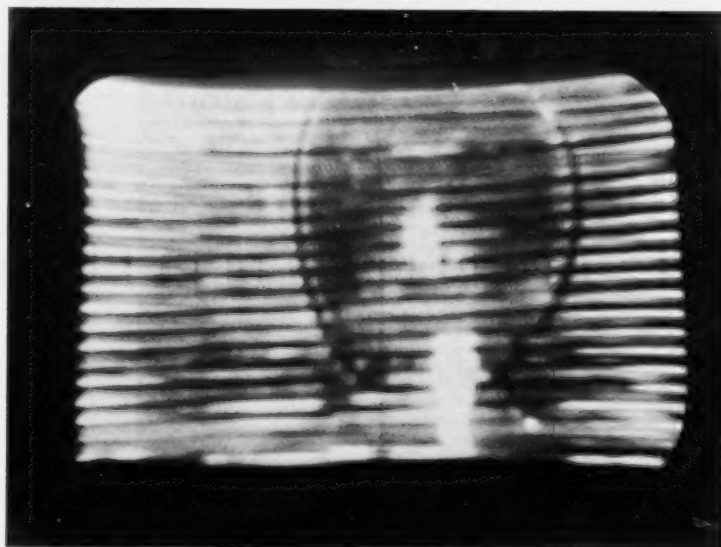


Figure 73. Diesel Fuel Oil No. 2 Being Added to Water Inside Ring

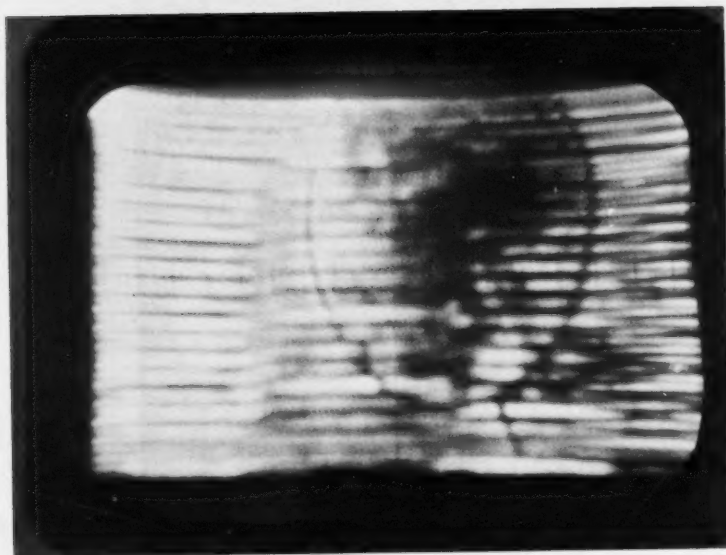


Figure 74. Diesel Fuel Oil No. 2 Spread Evenly Inside Ring

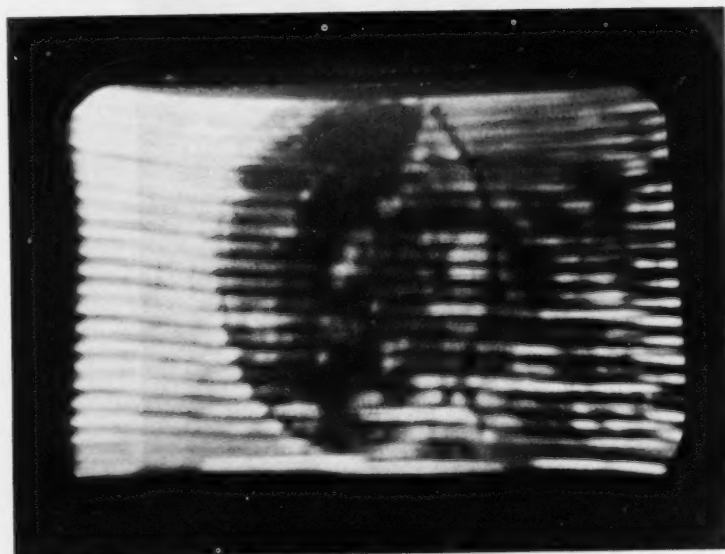


Figure 75. Diesel Fuel Oil No. 2 Sheen in Presence of Waves

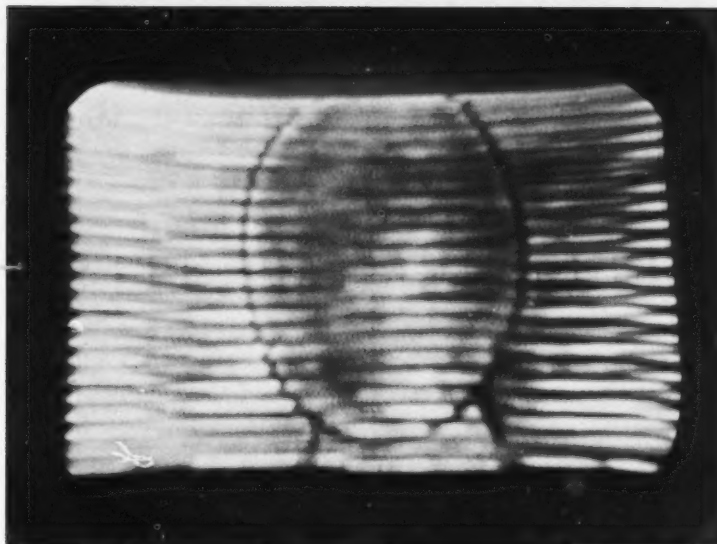


Figure 76. Plastic Ring in Clean Water Before Adding Diesel Fuel Oil No. 4

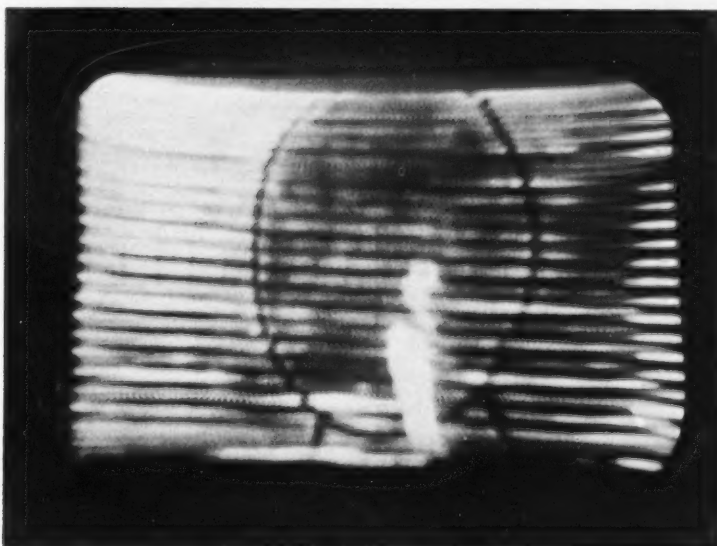


Figure 77. Diesel Fuel Oil No. 4 Being Added to Water Inside Ring

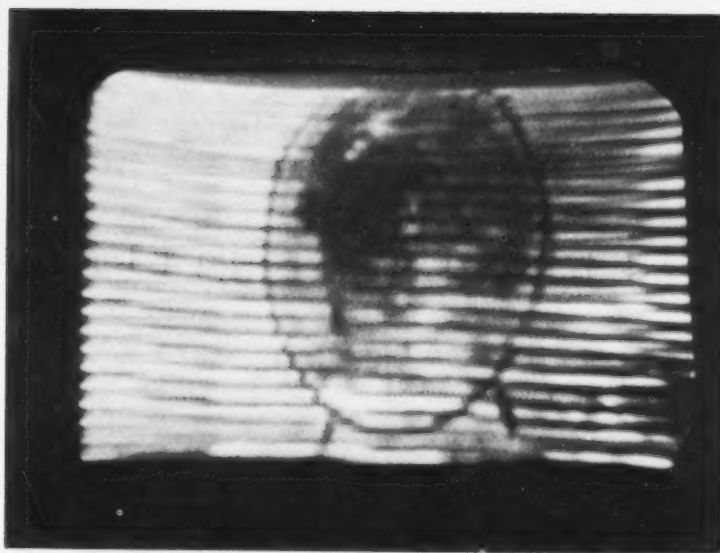


Figure 78. Patches of Diesel Fuel Oil No. 4 Sheen

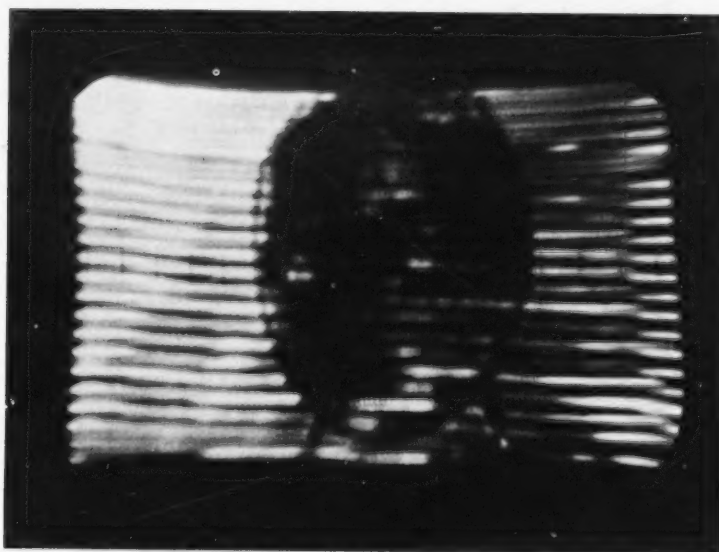


Figure 79. Diesel Fuel Oil No. 4 Spread Evenly Inside Ring

Florida crude oil was the fourth sample observed. Figure 80 shows 1/2 ounce of the oil poured inside of the ring. Note the heavy, bright thick spot remaining in tact. After awhile, the wind blew the oil to the upper right corner, as shown in Figure 81. Figure 82 shows the removal of a small portion of the oil to illustrate its effect in an area large enough to not limit its spread. Figure 83 shows light and dark spots spread over the entire area of the ring. The lumps did not disperse. Figure 84 shows a temporary sheen of oil after disturbance. Figure 85 shows lumps of oil coalescing into bright spots again after being left alone for a while. Figure 86 shows the oil sheen after most of the oil was removed with polyurethane foam chips.

These four samples illustrate how one could identify oil types by their signatures by merely classifying them by their physically observed characteristics. Table 11 shows the classification for the four oils, as observed.

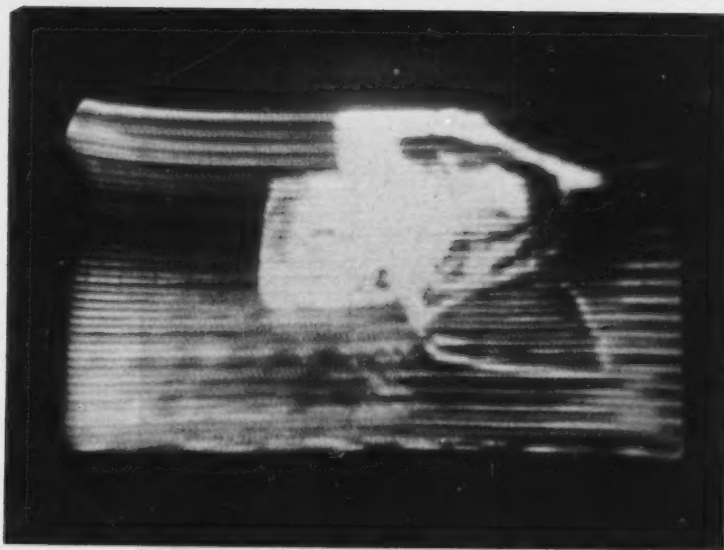


Figure 80. Florida Crude Oil Being added to Water Inside Ring

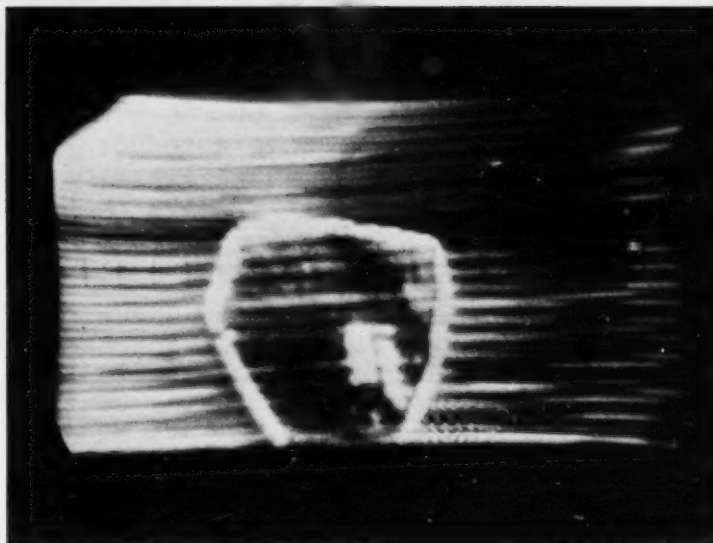


Figure 81. Florida Crude Oil Blown into Upper Right Corner
by Wind

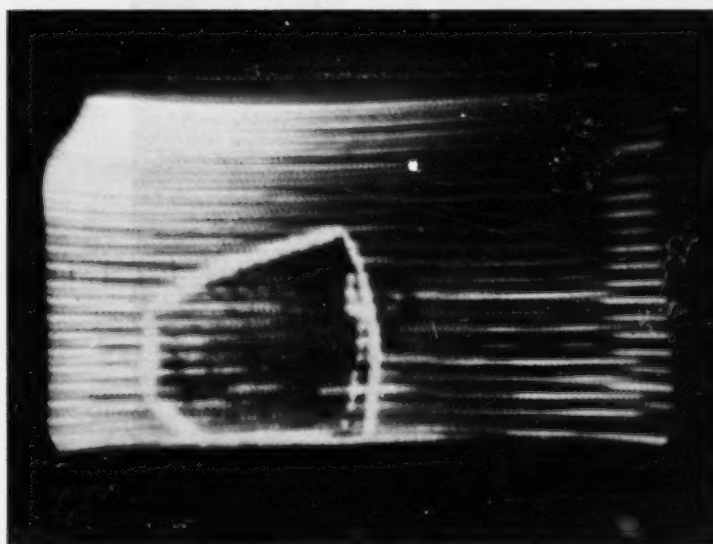


Figure 82. Small Portion of Florida Crude Oil Removed

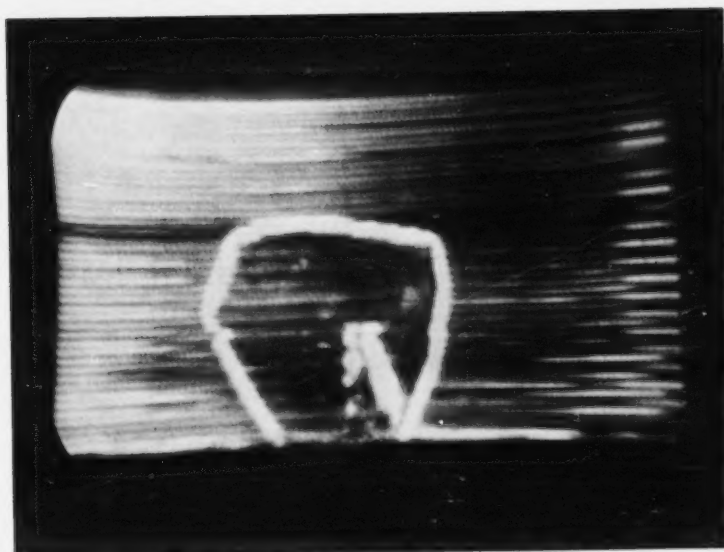


Figure 83. Thick and Thin Spots of Florida Crude Oil Undispersed Over Entire Ring

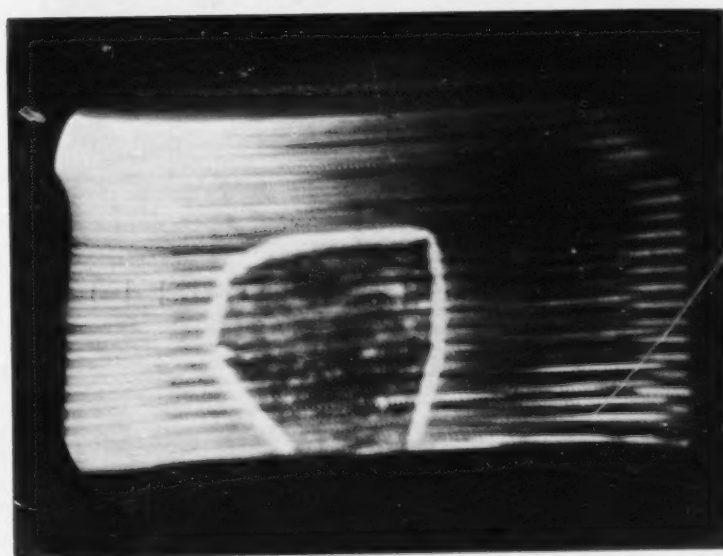


Figure 84. Temporary Florida Crude Oil Sheen After Disturbance

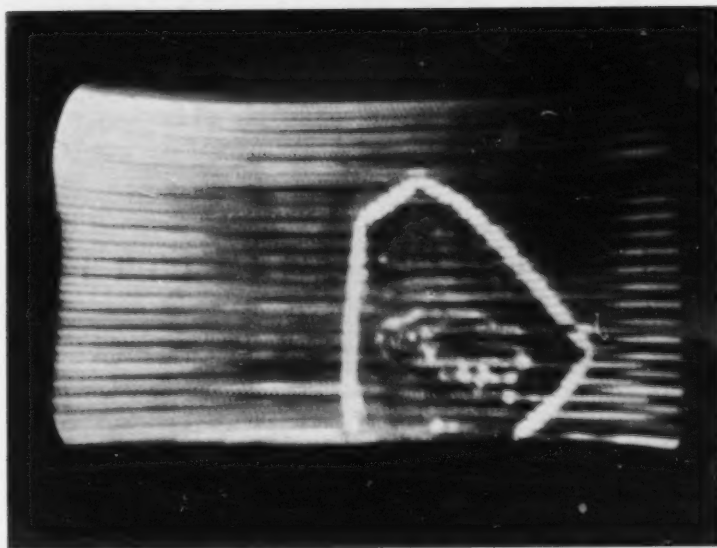


Figure 85. Lumps of Florida Crude Oil Coalescing Into Bright Spots

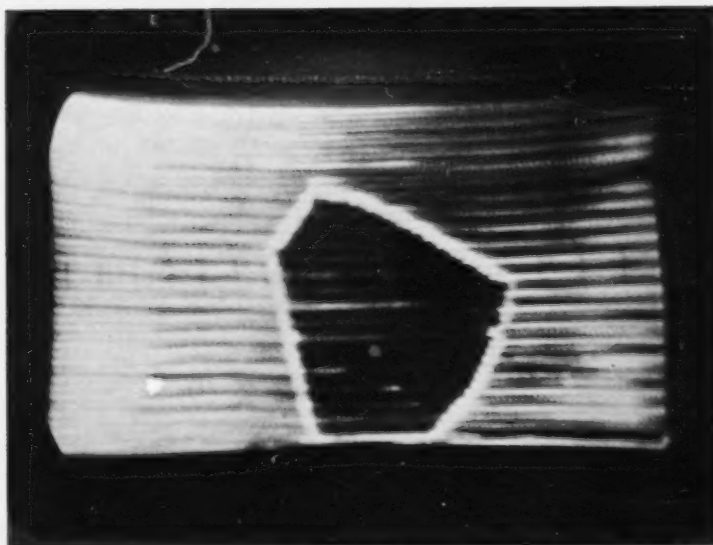


Figure 86. Florida Crude Oil Sheen After Removal of Most Oil

TABLE 11. OIL TYPE TABLE

<u>Characteristics</u>	<u>Navy Distillate</u>	<u>Diesel Fuel #2</u>	<u>Diesel Fuel #4</u>	<u>Florida Crude</u>
A. Lumpy even after Agitation	0	0	0	x
B. Light & Dark Initially	0	x	x	x
C. Spreads to Sheen Fast	x	x	0	0
D. Covers Entire Area Without Agitation	0	x	0	0

Thus, one can see how to identify diesel fuel oil number 2, for example. It exhibits characteristics B, C and D in Table 11, whereas, for example, Florida crude exhibits A and B. This method is not absolute or fool proof, as there are probably other oils not listed in the table that exhibit the same characteristics as one or more of the samples. The solution to that type of problem is to have a very large list of characteristics, and identify each known oil according to its differences from other oils. Even then, there is uncertainty due to environmental conditions.

This type of test is meant only to be a rough identifier.

One overriding point to be made in this test is that all types of oil tested could be seen with the exception of a light "overhead" oil. this one exception evaporated too fast for observation.

Time-Of-Day Test

A black body radiator radiates energy according to the Stephan-Boltzman Fourth-power law: $E_b = \sigma T^4$.

where E_b = Energy radiated from the black body per unit time per unit area exposed.

σ = constant of proportionality

T = Temperature (absolute) of radiator

A gray body, such as water or oil, radiates according to the following:

$$E_G = \epsilon_g E_b = \epsilon_g \sigma T^4$$

where ϵ_g is a constant for any particular material which indicates the quality of black body it is. Thus, the radiation of a material like the absorption, is a function of the emissivity ($\epsilon_g \sigma$) and the absolute temperature (T^4).

Let's apply the preceding to the experimental objects shown in Figure 87.

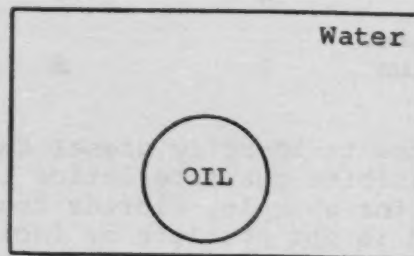


Figure 87. Oil - Water Test Configuration

The ambient temperature can heat or cool a small body of oil in a much shorter time than the water which the oil is in. As night falls, the ambient temperature drops; the water and the oil will start to cool with this drop in ambient temperature, but the oil is able to cool faster due to its smaller volume. Thus, the temperature of the oil will be lower than the temperature of the water at night, making the emission energy of the oil less than that for the water. Since less energy is being emitted from the oil than from the water, less energy is evident to the sensor. Thus, the ring of oil will appear dark with respect to the water at night. This would not necessarily be true if oil and water had better thermal conductivity at the boundary.

In the day, of course, the opposite is true. That is, due to the oil sample's ability to raise its temperature faster, it is a better radiator in the daytime. Thus, the oil appears as a bright spot compared to water, as shown in Figure 88.

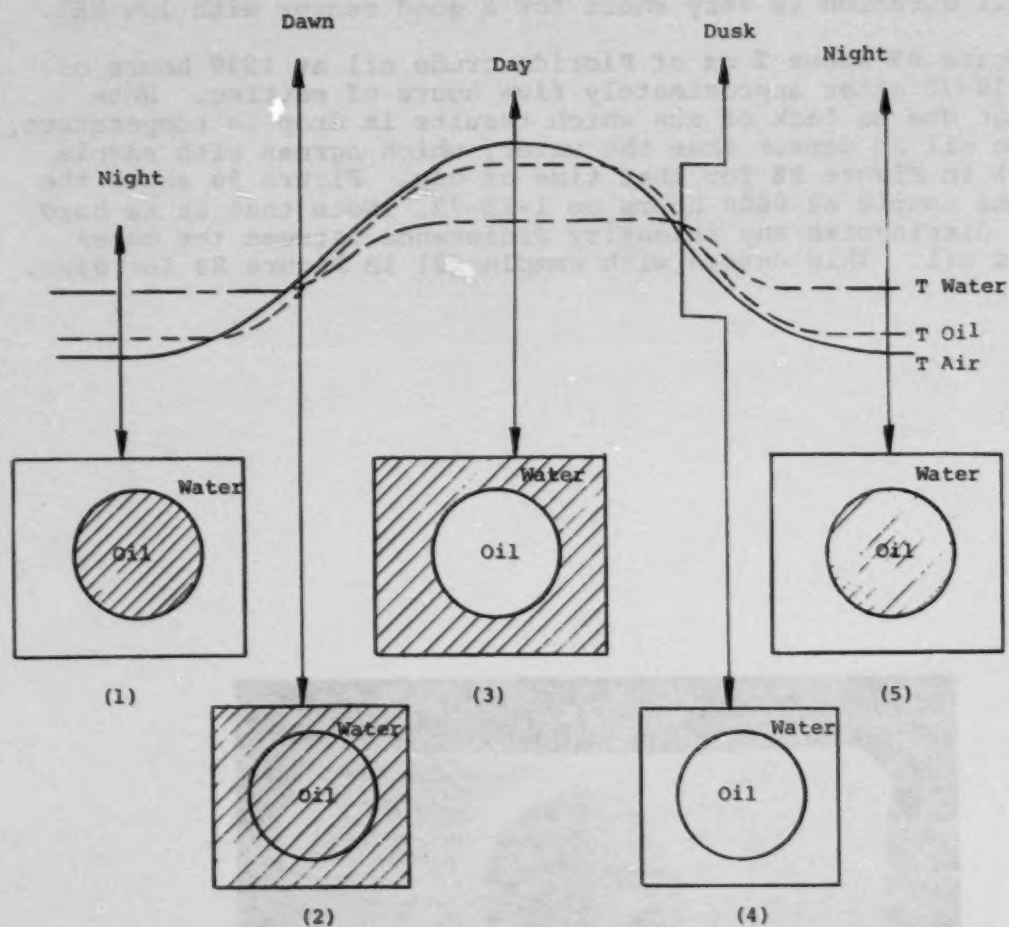


Figure 88. Temperatures of Water, Oil, and Air Over a Day's Time and the Corresponding Variations in Presentation

As can be seen in samples (2) and (4) in Figure 88, the water and oil cannot be distinguished from each other at two times in the diurnal cycle. This is at the time when the oil temperature and water temperature are equal during the transition portion of the diurnal cycle. Thus, at two times (of day) the passive sensor cannot be used effectively. This duration is very short for a good sensor with low NET.

Figure 89 shows 2 oz of Florida crude oil at 1830 hours on 1-18-72 after approximately five hours of setting. Note that due to lack of sun which results in drop in temperature, the oil is darker than the water, which agrees with sample (5) in Figure 88 for that time of day. Figure 90 shows the same sample at 0600 hours on 1-19-72. Note that it is hard to distinguish any intensity difference between the water and oil. This agrees with sample (2) in Figure 88 for dawn.

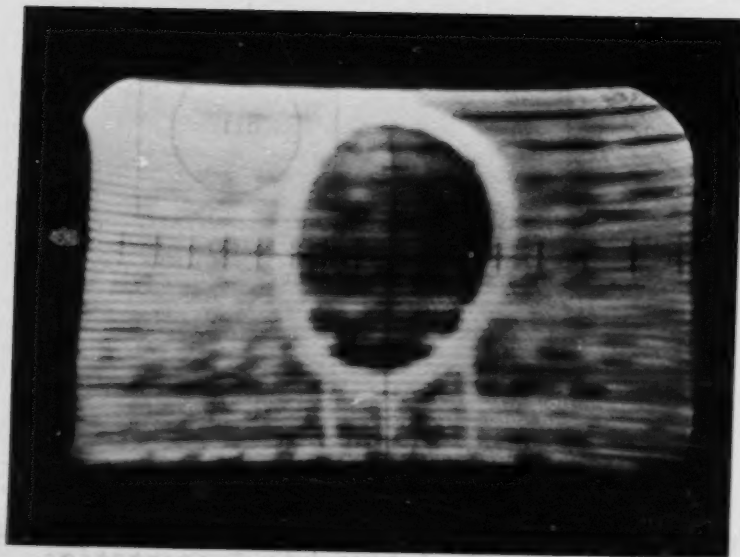


Figure 89. Florida Crude Oil on Water, 1800 Hours, 1-18-72

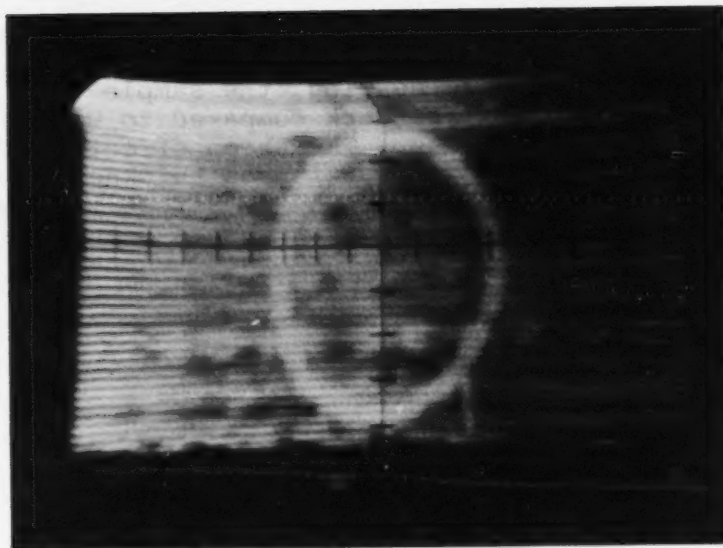


Figure 90. Florida Crude Oil on Water, 0600 Hours, 1-19-72

Figure 91 is taken at 0630 hours and still exhibits dawn characteristics. Figure 92 still exhibits the dawn characteristics of gray versus gray intensity. This was the last dawn shot taken at 0650 hours. Thus, for this sample and this system, the (indistinguishable) time lasted approximately 50 minutes. Figure 93 shows the same sample in the small ring taken at 0700 hours. The sun has heated the sample slightly. This corresponds to a region between samples (2) and (3) in Figure 88. Figure 94 shows the same sample, in the small ring, at 0730 hours. Note the increasing intensity as the oil heats up. Figure 95 shows the sample at 0900 hours. Note the high intensity of oil. Also note that the wind is blowing a small portion of the oil out. Figure 96 shows the same sample at 1100 hours. Notice that the intensity has not increased. This is probably the maximum temperature point of oil for that particular set of air and water temperatures and that particular ring area and wind speed. Figure 97 shows the sample at noon after some of the sample was blown away. There is also disturbance, as shown in Figure 98, due to the wind. Note that the sample is still fairly bright compared to the water.

Figure 99 shows the remaining sample at 1300 after wind is settled. Note that the sample is still fairly bright. Thus, the illustration in Figure 88 is well supported in Figures 89 through 99.

Many things can affect the results of a test like the one described in the preceeding paragraph. For example, if enough oil is blown out of the ring, the sample will exhibit a sheen effect, which appears dark compared to water, regardless of the time of day. The sheen effect will be discussed in detail in the subsection on thickness. The point is that many variables can and do affect the results of a particular test, and although much has been done to isolate variables, it is possible for some un-named variables to affect the test results somewhat.

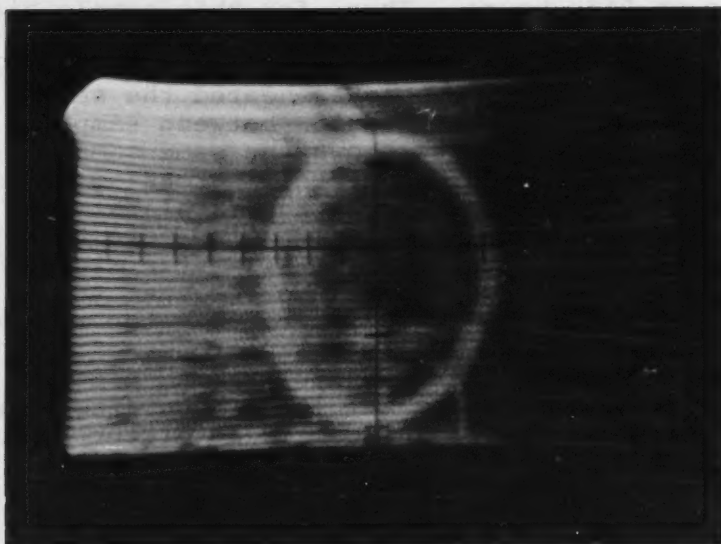


Figure 91. Florida Crude Oil on Water, 0630 Hours, 1-19-72

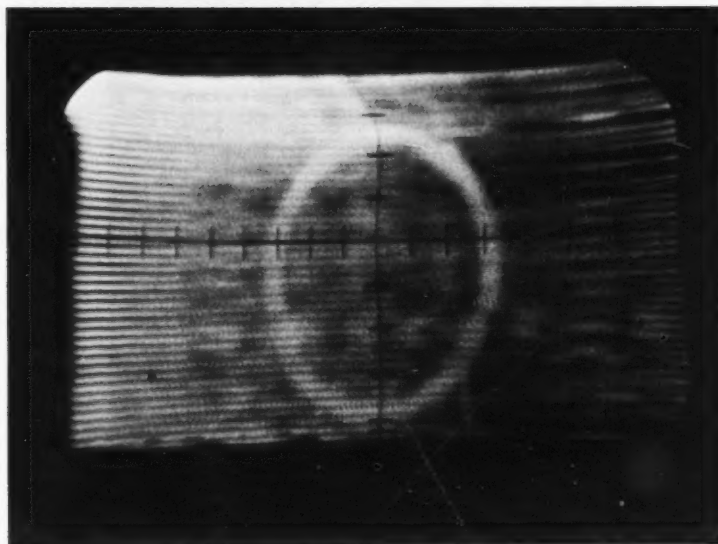


Figure 92. Florida Crude Oil on Water, 0650 Hours, 1-19-72

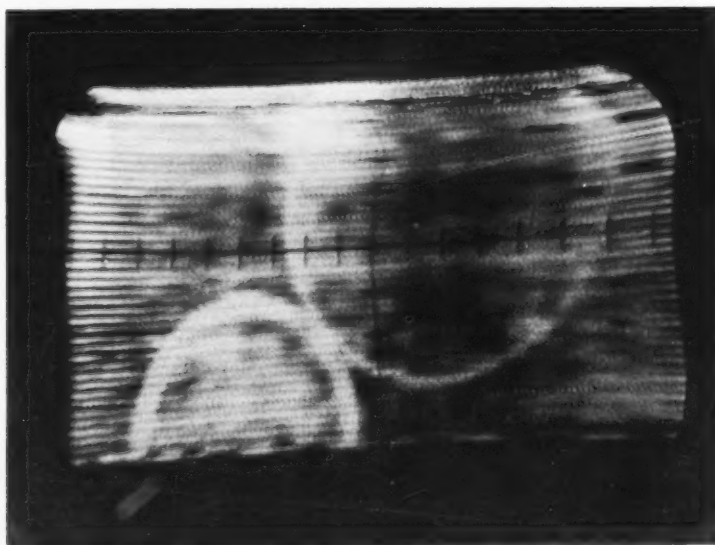


Figure 93. Florida Crude Oil on Water, 0700 Hours, 1-19-72

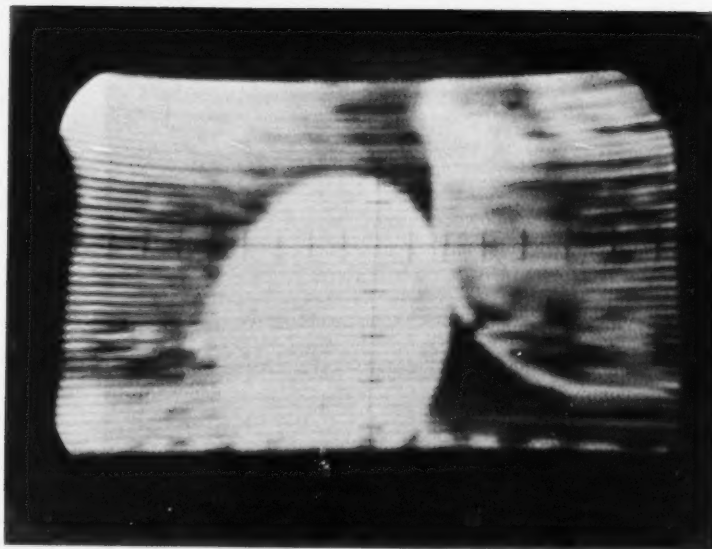


Figure 94. Florida Crude Oil on Water, 0730 Hours, 1-19-72

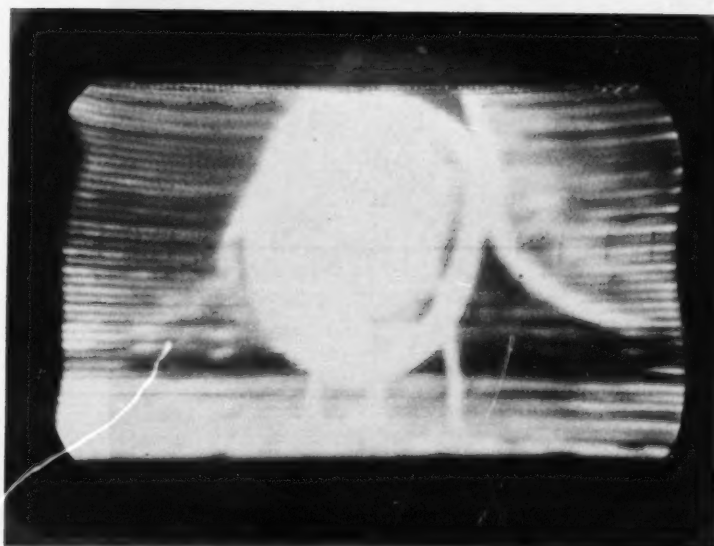


Figure 95. Florida Crude Oil on Water, 0900 Hours, 1-19-72

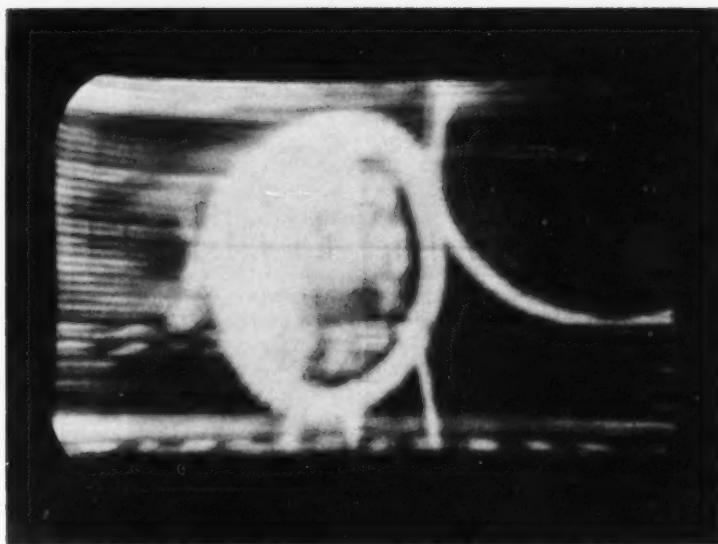


Figure 96. Florida Crude Oil on Water 1100 Hours, 1-19-72

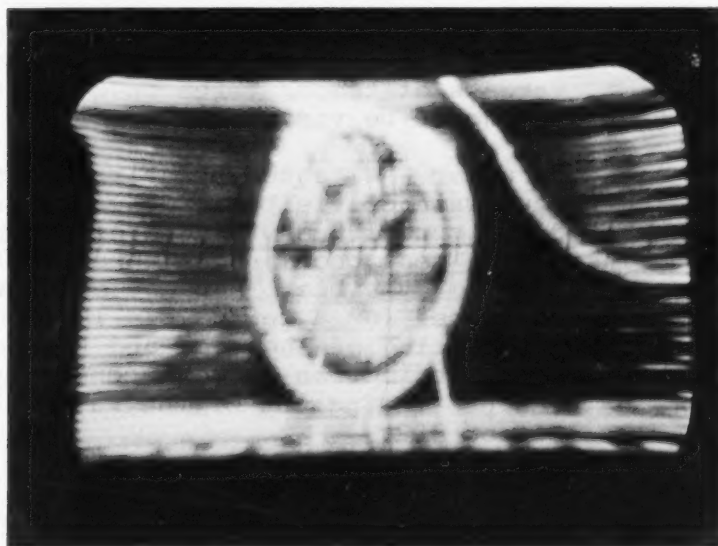


Figure 97. Florida Crude Oil on Water, Noon, 1-19-72

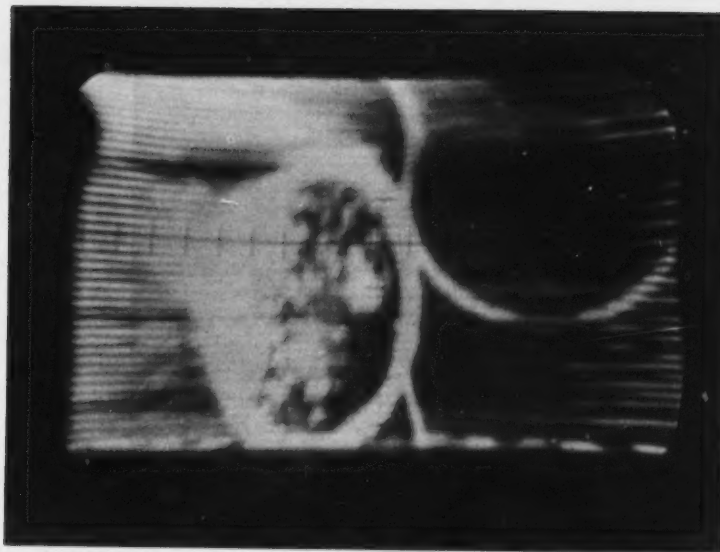


Figure 98. Some Florida Crude Oil Being Blown from Ring
Debris Test

Some selected tests were made to determine what types of debris, or non-oil types of material would be visible with the infrared sensor. Targets of temperatures or emissivities much greater than water should be visible.

The visibility of muddy water was tested by stirring up the mud in the lake. The mud was not visible. Seaweed, or its equivalent, was tested. Figure 100 shows a large clump of seaweed floating inside the test boom in the upper left quarter. The seaweed was not visible. A piece of plywood was put in the boom and soaked for a few days. The wood was visible due to the solar heating of the wood and the solar reflection from the wood. Reflection is most conspicuous on the portions of the wood protruding out of the water. This is shown in Figures 101 and 102.

Ice is visible as very dark, sharply outlined objects in both the day and night which makes it easy to differentiate from oil.

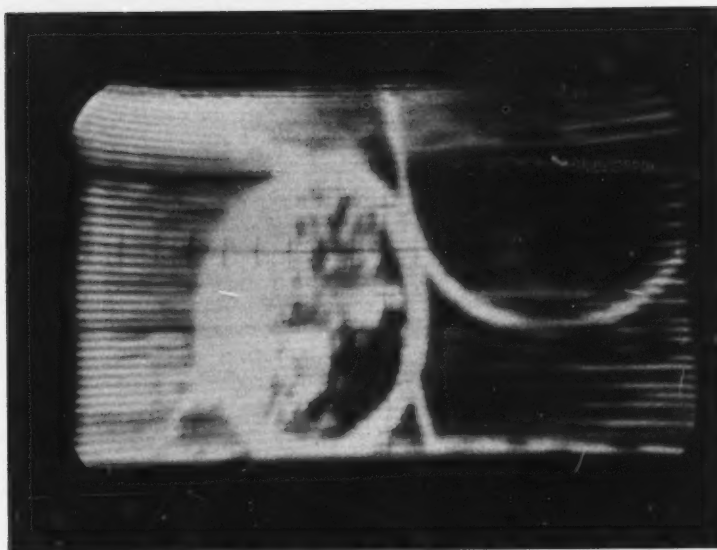


Figure 99. Florida Crude Oil on Water, 1300 Hours, 1-19-72

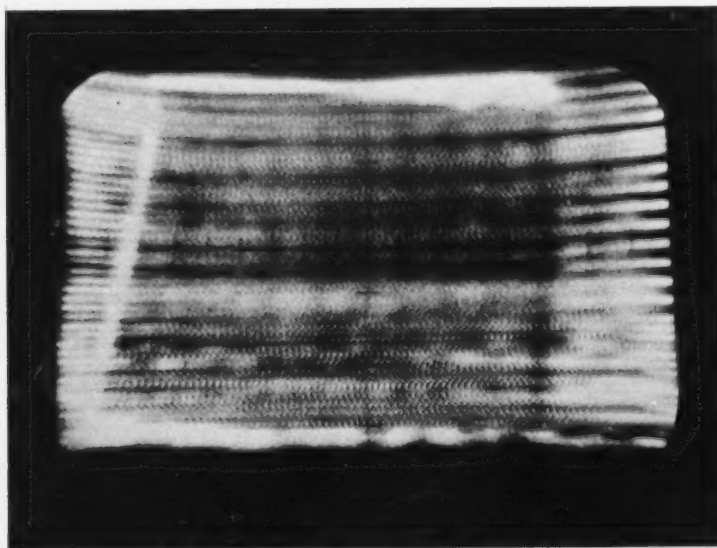


Figure 100. Seaweed Sample

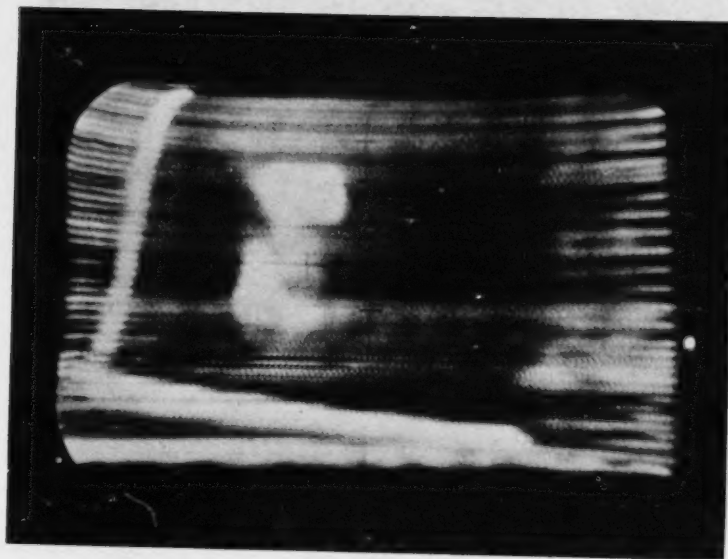


Figure 101. Plywood in Water

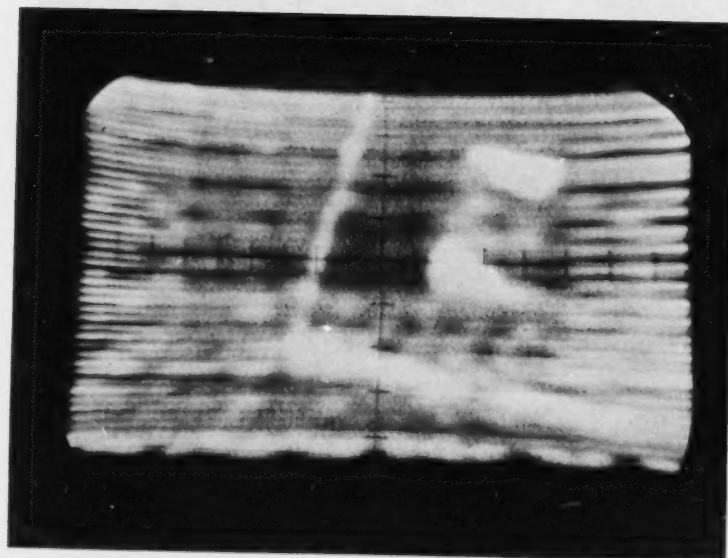


Figure 102. Plywood in Water After One Week

In general, there are a few classes of materials which are visible. One class includes those materials capable of reflecting thermal radiation. Another class includes those materials with good thermal absorption properties and poor thermal conductivity with water. This enables the latter material to store heat; thus, it will have a higher temperature. All oils fall into this category. Not many other materials existing in large quantity on the ocean surface fall into this category.

All single or solid objects have definite, unchanging silhouettes and are not large enough to be mistaken for an oil spill.

Thickness Test

The volume of a particular sample of oil on water is the product of its thickness and its surface area of contact with the water. Thus, for a given volume of oil, the greater the thickness, the less surface area in contact with the water. A water-oil boundary has low thermal conductivity. Thus, for a sufficient amount of heat to be transmitted through the boundary to allow the temperature of the oil to follow the water temperature the contact area must be large. The larger the volume of oil, the more heat is necessary to raise or lower the oil temperature. This means that in order to transport sufficient heat across a water-oil boundary to allow the oil to follow the water temperature, the volume must be small in proportion to the contact area or the contact area; in proportion to the volume, must be large. Since thickness is volume divided by surface area, a thin sample of oil will meet the criterion mentioned above, and the temperature of a sufficiently thin sample of oil should follow the temperature of the water.

The thermal emissivity of water is greater than that of oil. Thus, if a sample of oil is on the water, sufficiently thin to allow its temperature to follow the temperature of the water, the oil should appear darker than water to an infrared sensor. A material of a certain temperature and emissivity will emit less heat than another material of equal temperature, but higher emissivity.

From the preceding discussion, it is clear that a thin sheen of oil on water, which has had sufficient time to reach the temperature of the water, should appear dark with respect to the water as seen from an infrared sensor.

Conversely, a thick layer of oil should appear brighter than water in the daylight and darker than water at night. The reason for this was discussed in the section on time-of-day

test. Thus, for a typical daytime experiment, with any particular type of oil, the brightness of the oil should vary from the same as water when thickness is zero, to less than water for thin sheen, to greater than water for thick layer.

To isolate sample thickness as the variable by eliminating wind, waves and solar radiation, a laboratory environment was used.

The oil thickness variable was controlled by placing water of equal volume into two identical containers and adding crude oil to one container using a hypodermic syringe. The syringe was graduated in cubic centimeters; therefore, by knowing the surface area of the water, the oil thickness could be determined. This method of determining thickness, of course assumes a uniform distribution of the oil. To insure this, the sample was selected to disperse rapidly and to cover the entire area of the water surface. The sample chosen was crude oil from the Jay Field in Florida, donated by Sun Oil Company, Richardson, Texas.

The 8- to 14-micron sensor was set up to view the water and oil-on-water samples perpendicular to the surface. Figure 103 illustrates the test configuration.

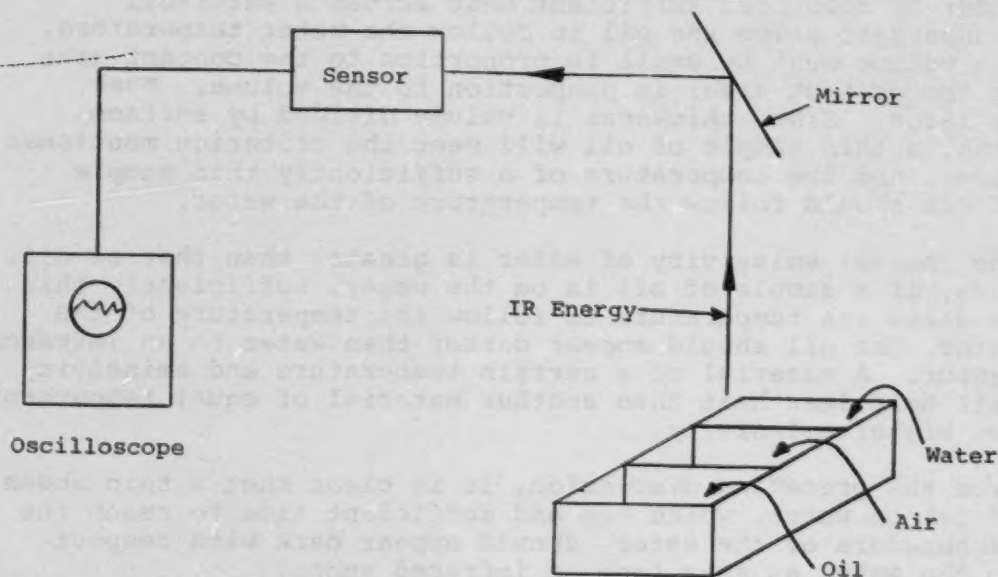


Figure 103. Oil Thickness Test Setup

The center channel of the sensor detector array was displayed on an oscilloscope where voltage measurements were made. The sensor has been previously lab calibrated using a controlled-temperature black body source (4°C per volt). Figures 104 through 115 are the actual data for thicknesses from 0 to 270 microns. Figure 104 shows the oscilloscope presentation of a center channel. Voltage is read from the curve by measuring the distance between a line drawn through the trough on the left (oil) and a line drawn through the trough on the right (water). Notice that the "hump" between them is the empty center trough.

Figure 105 shows the corresponding television video. Due to misalignment in the oscilloscope, it is necessary to use the parallel line method instead of reading the face of the oscilloscope directly. Figure 104 shows no oil. When the two parallel lines are formed through right and left they will meet. Figure 106 shows 0.25 micron thickness of oil on the left side. Notice the parallel line drawn on the left trough (L) is lower by 0.33°C than the parallel line on the right trough (R). Figure 108 shows 1.45 microns of thickness on the left. Notice that (L) is almost 0.5°C lower than (R). Notice the contrast difference between (R) and (L) in Figure 108. Figure 110 shows 16.5 microns of thickness on the left. Here, the oil has passed the optimum thickness for lowering the heat emission of the oil with respect to the water. Notice that (L) is only 0.1°C below (R). Figure 112 shows 140 microns of thickness on the left. Notice that the oil now appears hotter than water. (L) is 0.5° higher than water. Figure 114 shows 270 microns of thickness on the left. Here, (L) is 1.25°C higher than (R).

The apparent temperature of the oil surface with respect to water as a function of the thickness is shown in Figure 116. This curve was found to be repeatable for the given surroundings. However, as discussed in previous reports, variations in environmental conditions are the controlling factors.

Range Test

The effect of increased range is dominantly a slant angle characteristic rather than a distance characteristic, unless the infrared sensor is operating in a highly absorptive atmosphere. Slant angle affects the emissivity and reflectivity characteristics of a surface as seen by the sensor. Figure 117⁸ shows the variation of reflectivity and emissivity versus angle for a smooth water surface for three wavelengths (8, 11 and 12.5 microns). From this graph it is apparent that emissivity is significantly reduced at slant angles greater than 70 degrees. Correspondingly, reflectivity is increased significantly at this angle. Thus, at angles greater than 70 degrees it becomes increasingly

difficult to receive energy from the surface of the water. For this reason, it becomes very difficult to detect thermal anomalies at angles above 70 degrees.

With the sensor employed on this experiment, imagery at approximately 85 degrees slant angle was recorded. Figure 118 shows 2 ounces of Florida crude oil in 10- foot by 10-foot frame at 43 degrees slant angle which corresponds to a slant range of about 40 feet. Note the excellent clarity of the three gray shades. Figures 119 and 120 show 2 ounces of Florida crude oil in a frame at a slant angle of 60 and 70 degrees, which correspond to slant ranges of 60 and 88 feet respectively. Note the clarity of the three gray shades indicating thick oil, thin oil, and water in the 70 degree presentation.

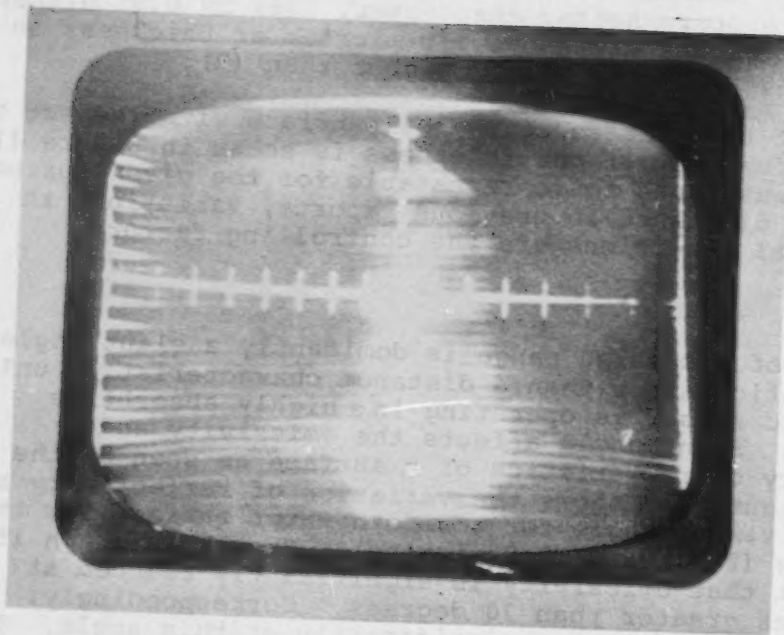


Figure 104. No Oil as Presented on Television Display

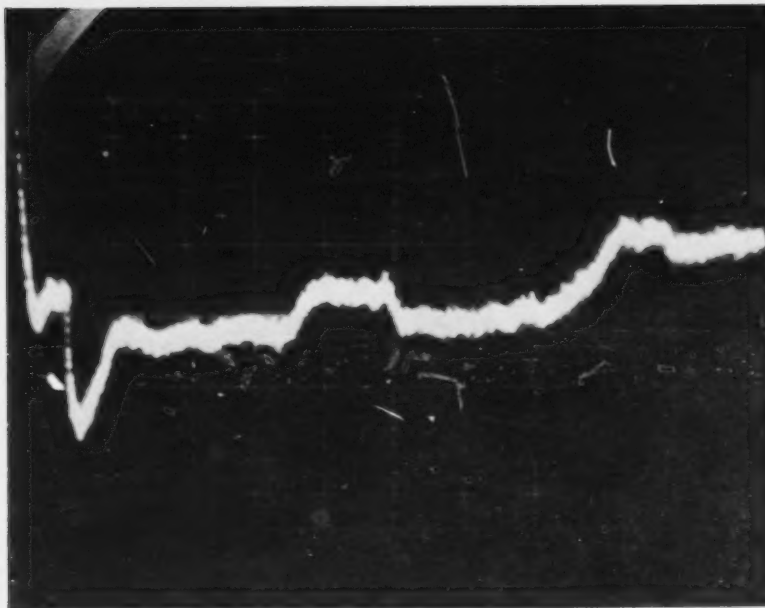


Figure 105. No Oil as Presented on Oscilloscope

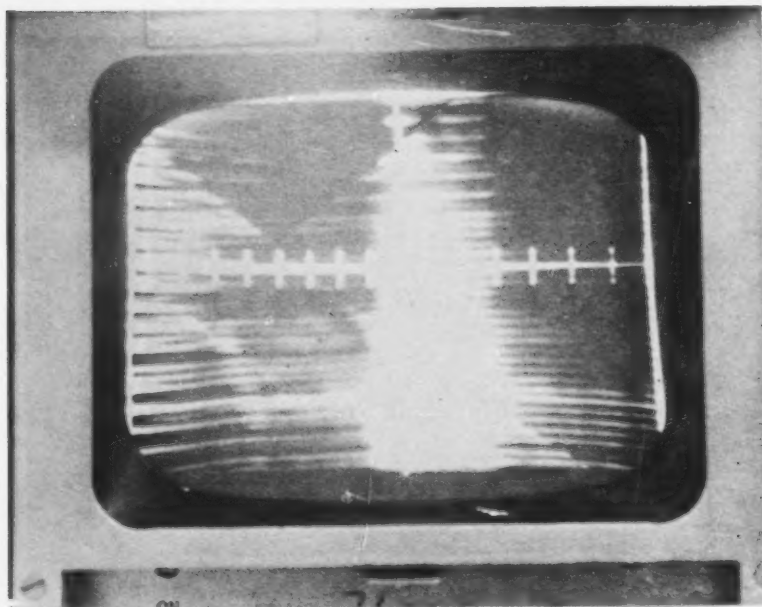


Figure 106. 2 Drops Florida Crude Oil as Presented on Television Display

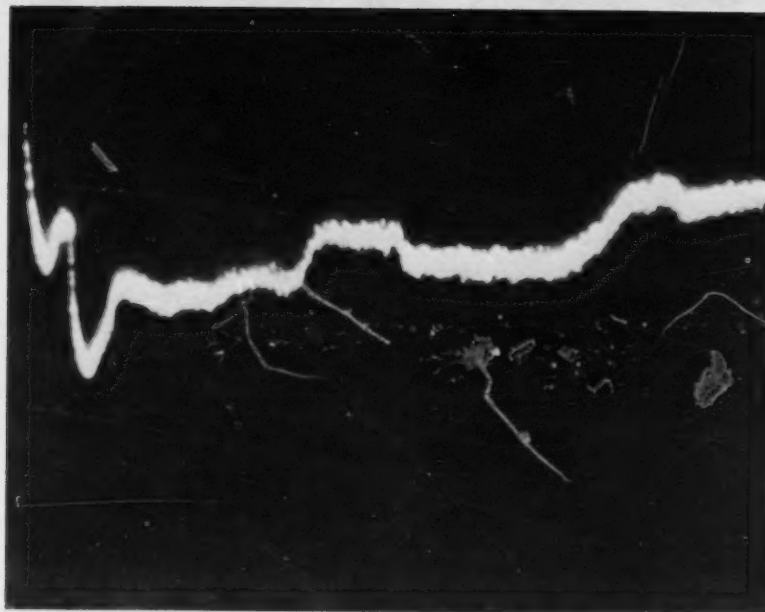


Figure 107. 2 Drops of Florida Crude Oil as Presented on Oscilloscope

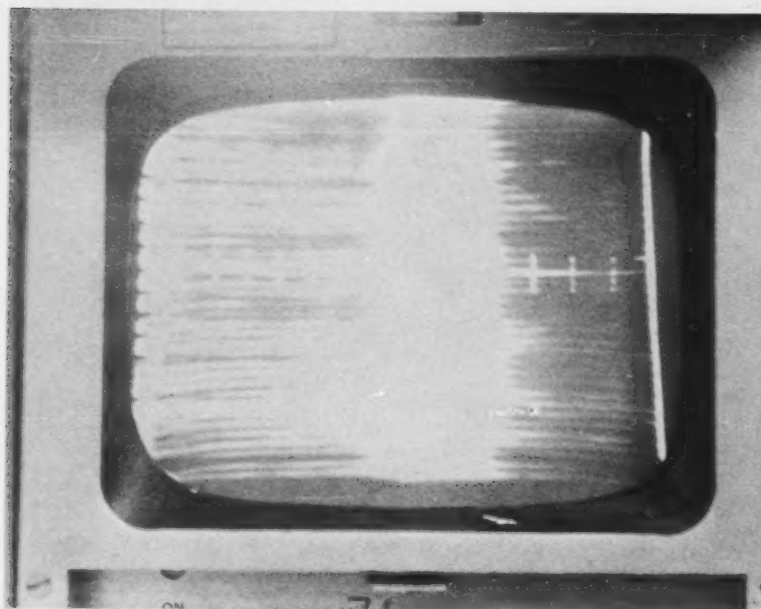


Figure 108. 4 Drops of Florida Crude Oil as Presented on Television Display

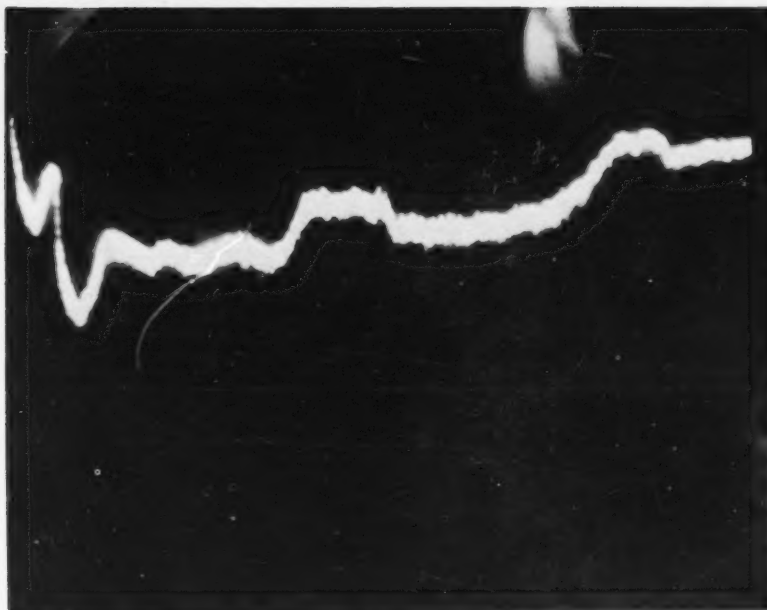


Figure 109. 4 Drops of Florida Crude Oil as Presented on Oscilloscope

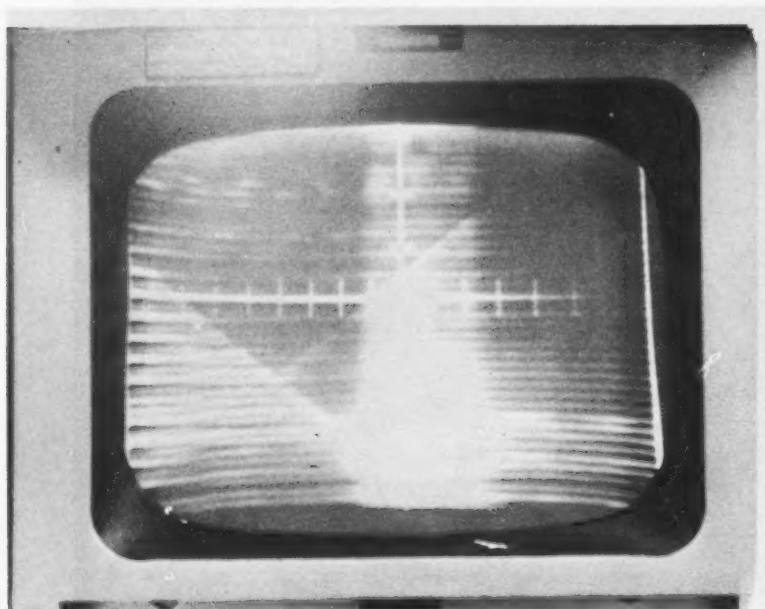


Figure 110. 8 Drops of Florida Crude Oil as Presented on Television Display

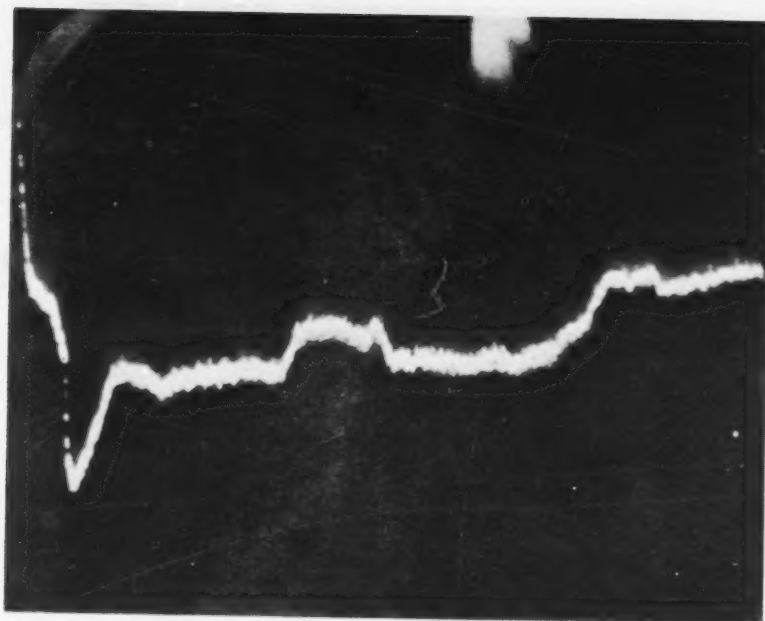


Figure 111. 8 Drops of Florida Crude Oil as Presented on Oscilloscope

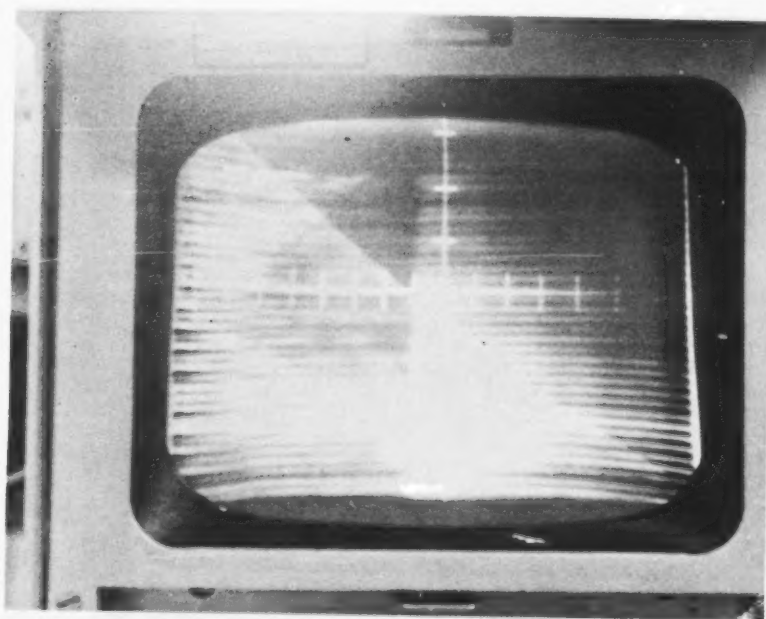


Figure 112. 2 Cubic Centimeters of Florida Crude Oil as Presented on Television Display

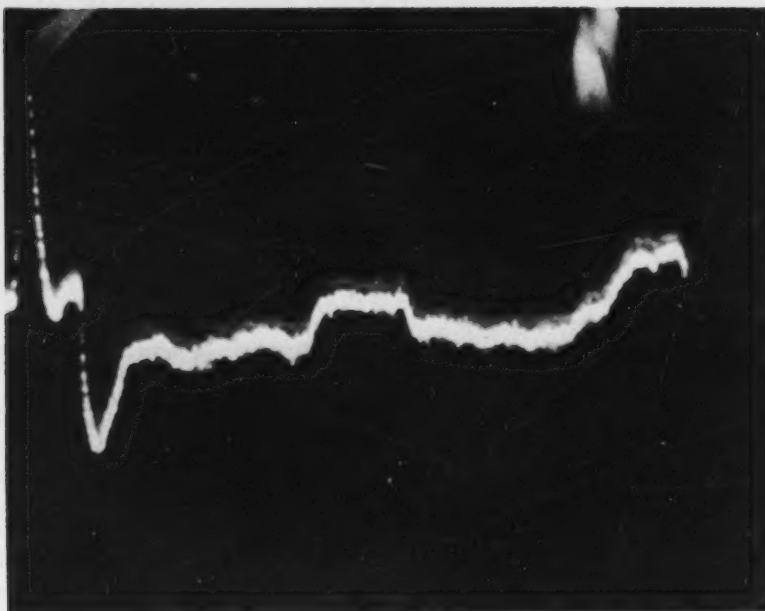


Figure 113. 2 Cubic Centimeters of Florida Crude Oil as Presented on Oscilloscope

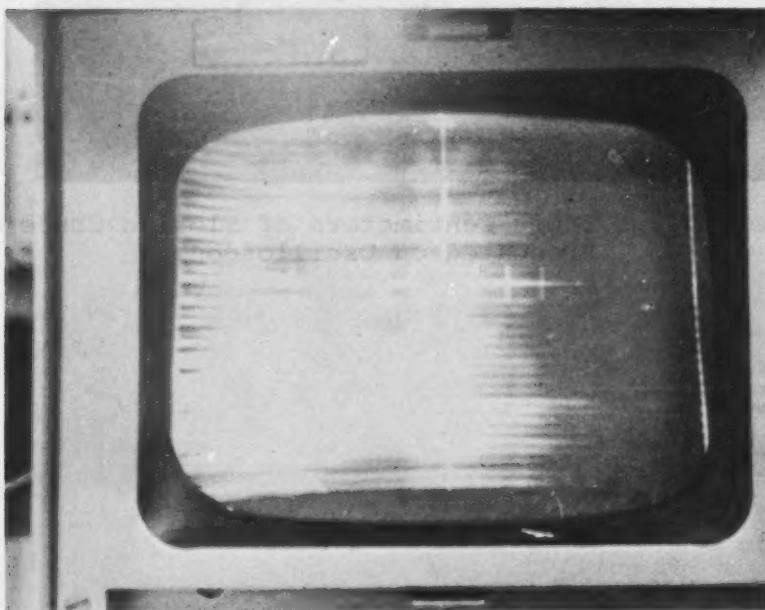


Figure 114. 5 Cubic Centimeters of Florida Crude Oil as Presented on Television Display

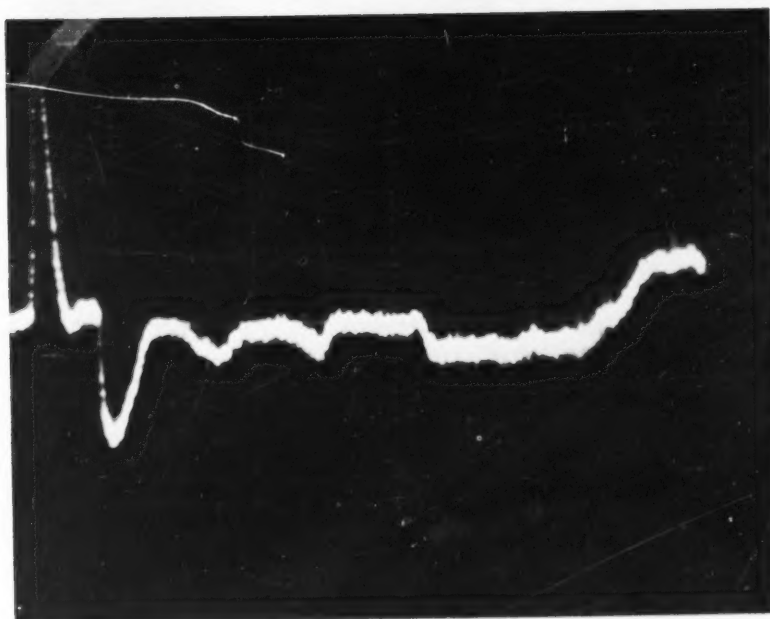


Figure 115. 5 Cubic Centimeters of Florida Crude Oil as Presented on Oscilloscope

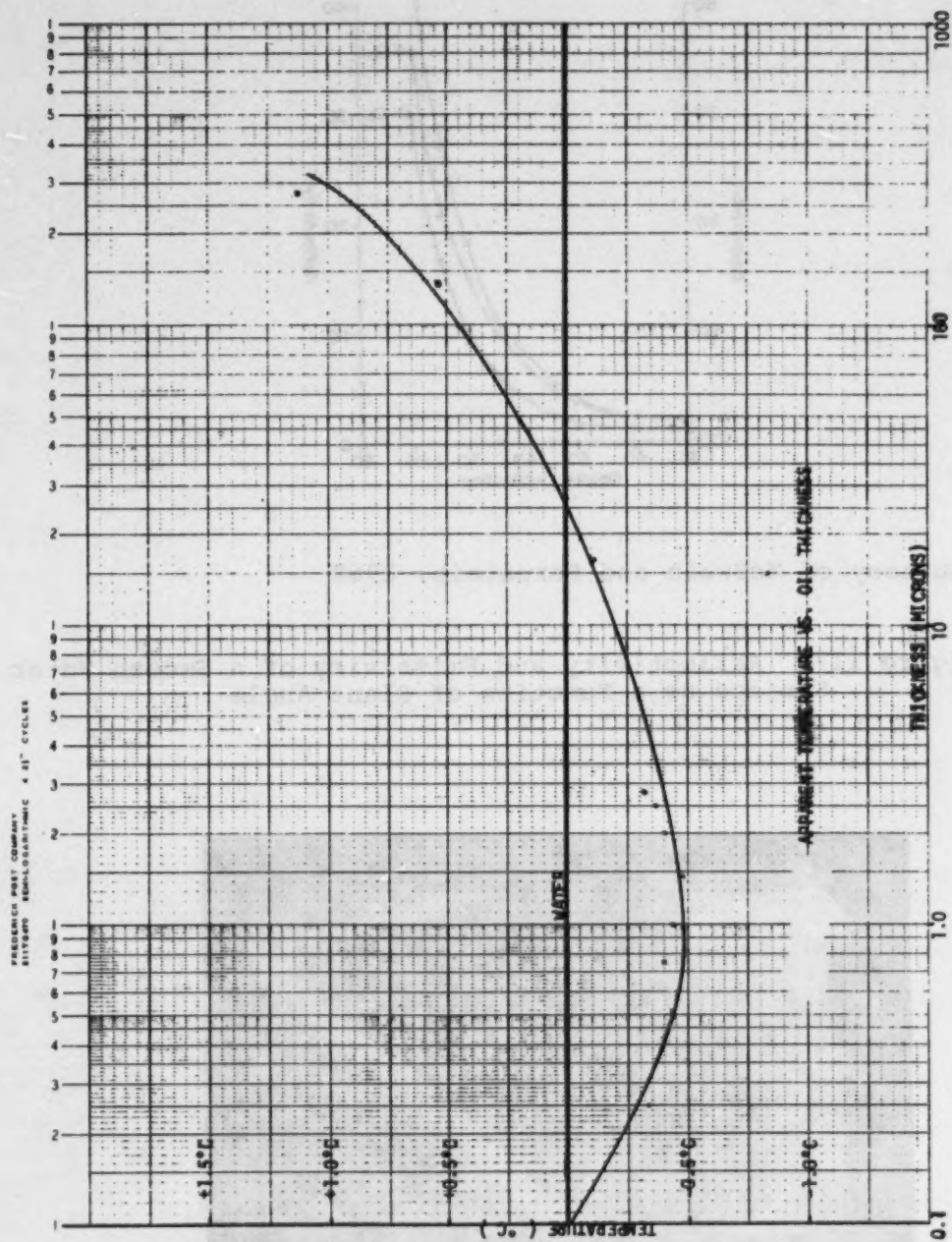
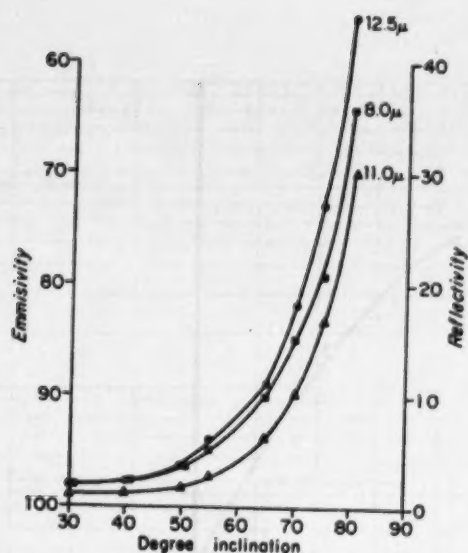


Figure 116. Apparent Temperature Versus Oil Thickness



Courtesy of McSwain and Bernstein, 1960

Figure 117. Reflectivity and Emissivity of a Smooth Water Surface as a Function of Slant Angle

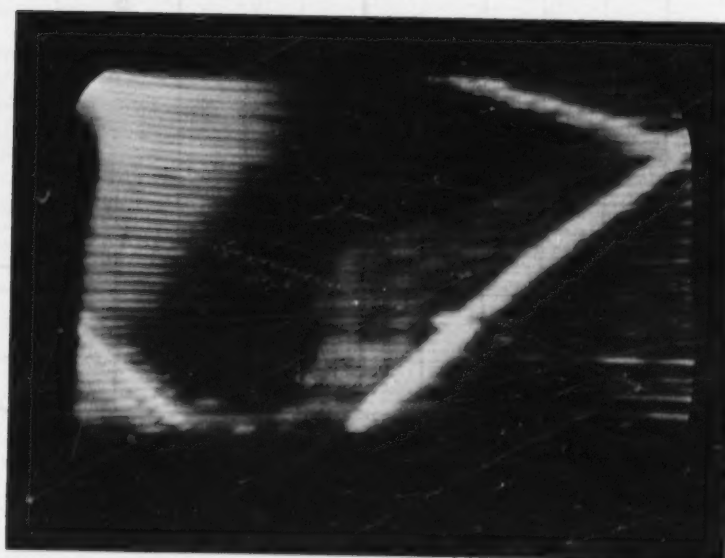


Figure 118. 2 Ounces of Florida Crude Oil at 43 Degrees Slant Angle

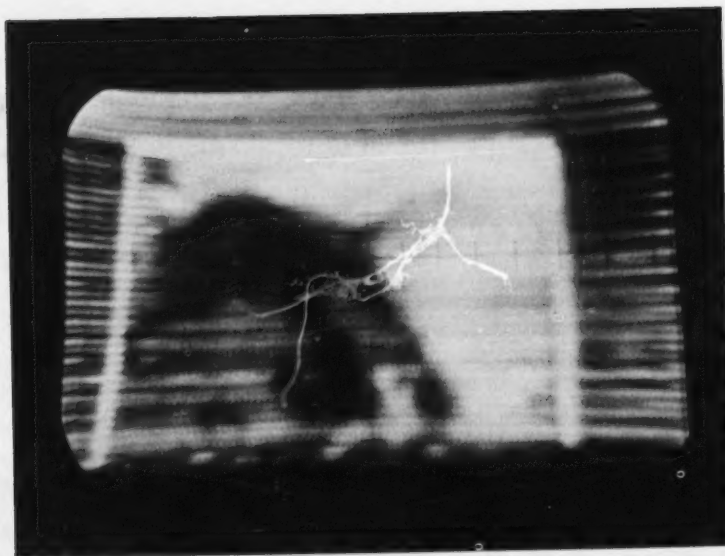


Figure 119. 2 Ounces of Florida Crude Oil at 60 Degrees
Slant Angle

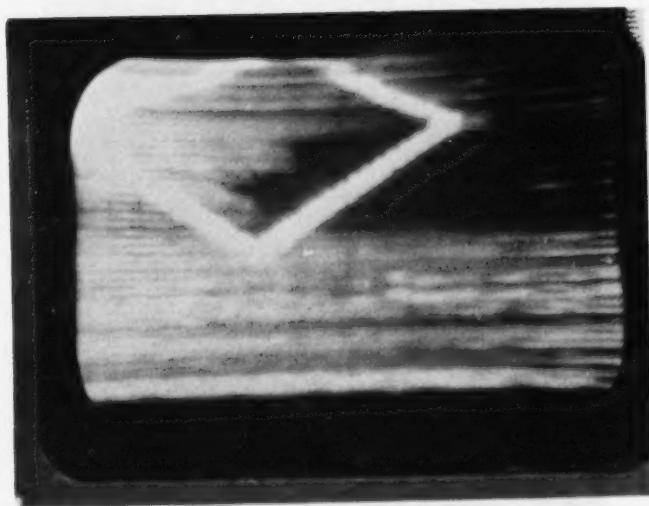


Figure 120. 2 Ounces of Florida Crude Oil at 70 Degrees
Slant Angle

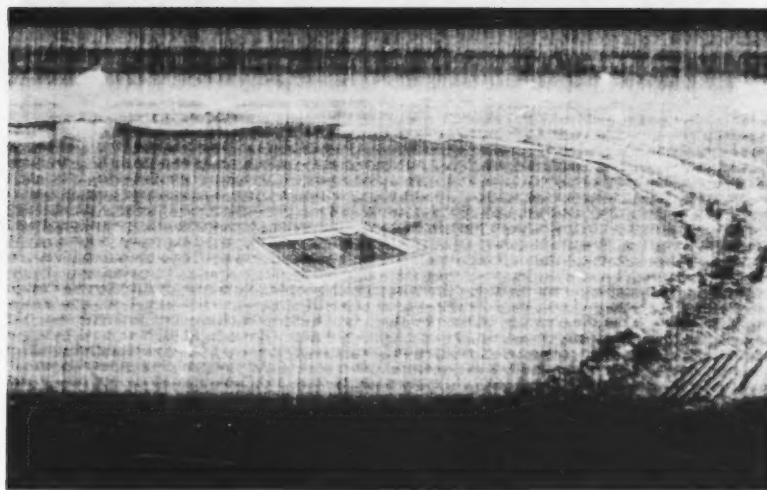


Figure 121. Waves at a Slant Angle of 86 Degrees

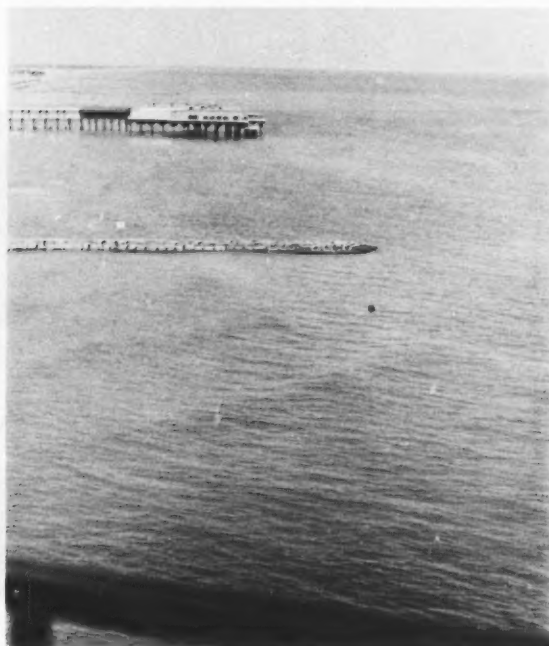


Figure 122. Galveston Bay as Seen From the Flagship Hotel

Later, samples at greater slant angles were observed with some success. At the testing site, another infrared sensor was tested for comparison. Figure 121 shows waves at approximately 200 feet horizontal range. The sensor was approximately 14 feet above the water surface. This is a slant angle of approximately 86 degrees. Note the clarity of wave action at approximately 86 degrees angle or 200 feet range. Figures 122 through 124 show imagery at the same approximate slant angle, but a far greater range. Figure 122 shows the view of Galveston Bay as seen from the Flagship Hotel. Note the sign on the jetty, the farthest pier, and the three posts protruding from the water at the end of the farthest pier.

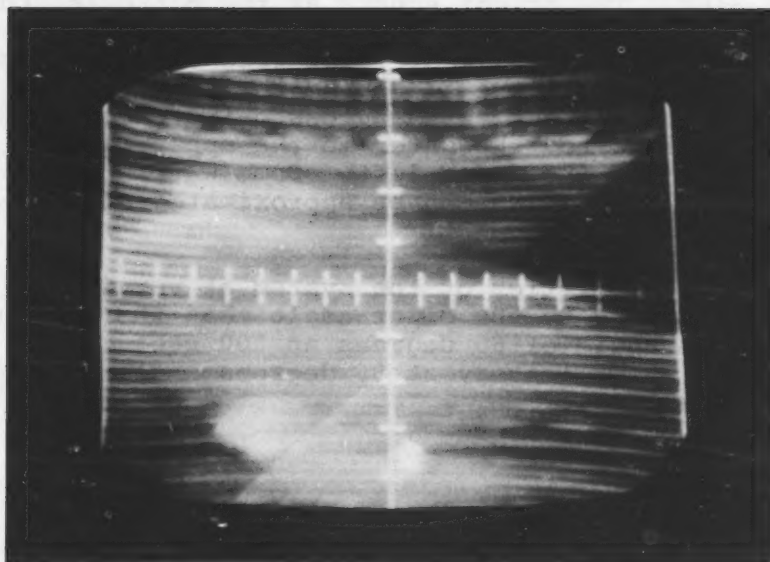


Figure 123. Galveston Bay at Slant Angle of 70 Degrees

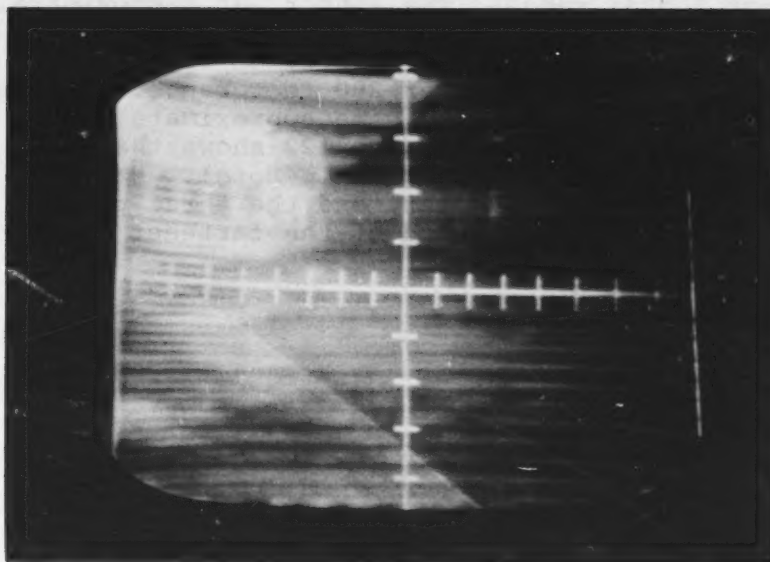


Figure 124. Galveston Bay at Slant Angle of 86 Degrees

Figure 123 shows imagery taken with the sensor at 70 degrees slant angle from approximately 90 feet above the water surface. The vertical lines at the top of the picture are the supporting members of the pier. The bright square at the bottom of the picture is the sign on the jetty. The bright spots to the left are wave action at an angle of 70 degrees and a horizontal range of over 400 feet. Figure 124 shows the imagery of the bay at an angle of 86 degrees at the cross hairs. Note the three posts protruding from the water in the upper right corner, and the pier in the upper left. Some wave action is shown in the lower left, which can be approximated at above 80-degrees angle.

Thus, the imagery capabilities of the system at varying ranges are affected more by the slant angle than the distance. Figure 121 shows an angle of 86 degrees at 200 feet, whereas Figure 124 shows imagery at 86 degrees angle at over 1000 feet horizontal range.

substantially increase the acoustical noise, and would introduce forced vibrations to the components. The natural-convection heatsink would be slightly larger, but would weigh only 12 ounces and be totally passive in operation.

The heat dissipation capability of the natural-convection heatsink is limited by fin surface area rather than internal thermal conduction. Therefore, this type could be fabricated of aluminum instead of a material with a higher thermal conductivity without loss in heat dissipating efficiency. This natural-convection heatsink is proposed for use on the 3- to 5-micron PbSe detectors.

SECTION IX

SYSTEM CONCEPTS, ACTIVE SENSOR

Introduction

Unit sensor cost is an important factor in the oil spill surveillance system concept and application study. When the unit cost for the active sensor is considered, it has been determined that this system is optimum for applications where a staring or limited scanning capability is required. Examples are estuaries, drainage channels, offshore drilling platforms and separator platforms. In this section, the system concepts for these applications will be discussed in the general terms of performance versus height, scan angle and meantime between failure. The specifics of which system for a given application and cost analysis are presented in Section XI.

Sensor Capabilities

The previous sections discussed the optical efficiencies of MOD 2 and MOD 3, both from a theoretical and experimental point of view. These results are summarized in Figures 125 through 130. In these figures, the expected signal-to-noise ratio for two system MODs are shown for three different altitudes as a function of scan radius. The graphs show the point at which the signal reaches such a low level that processing will no longer distinguish oil from water as discussed in Section VII. These points are indicated by a dashed line. The break points for several detector-filter combinations have been used (See Table 5). The detector temperatures of 243°K and 193°K can be achieved by using thermoelectric coolers which have relatively low cost. For 77°K operation in the field, an open cycle cooler is recommended. Note that there is an uncertainty in the values for PbSe and InSb when cold filtering is used since this is dependent upon detector selection.

The curves in Figures 125 through 130 are based on a combination of measured and extrapolated data for the case of smooth wave action. This was typical of cases at the Texas Instruments test facility where the waves did not have crests. On the basis of the test performed at the Gulf of Mexico, these curves are conservative. For normal incidence, that is zero scan radius, the smoother the surface the larger the signal-to-noise ratio will be. From the Gulf of Mexico test it was found that for the normal wave action the

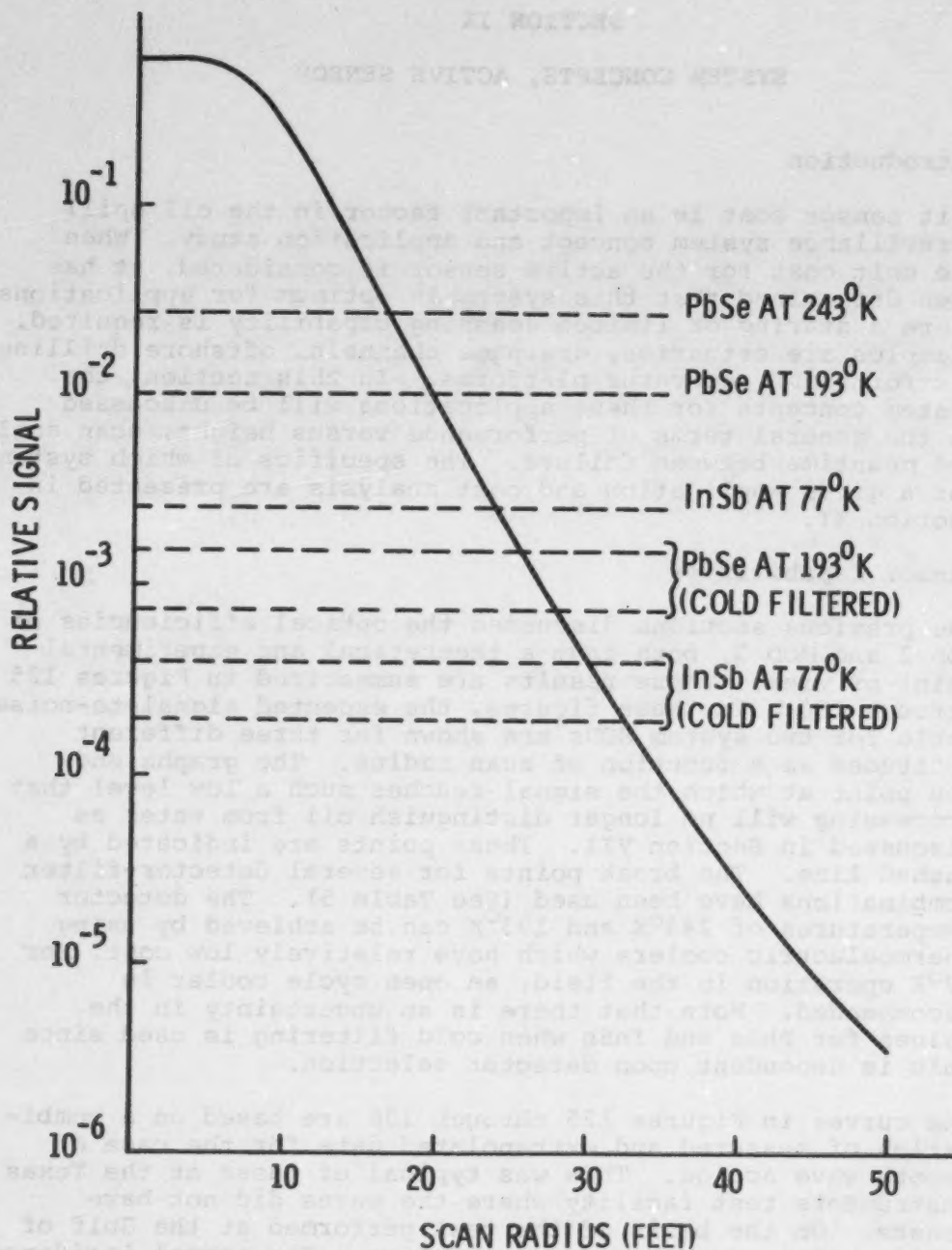


Figure 125. Signal Versus Scan Radius for MOD 2 at 50-Foot Altitude

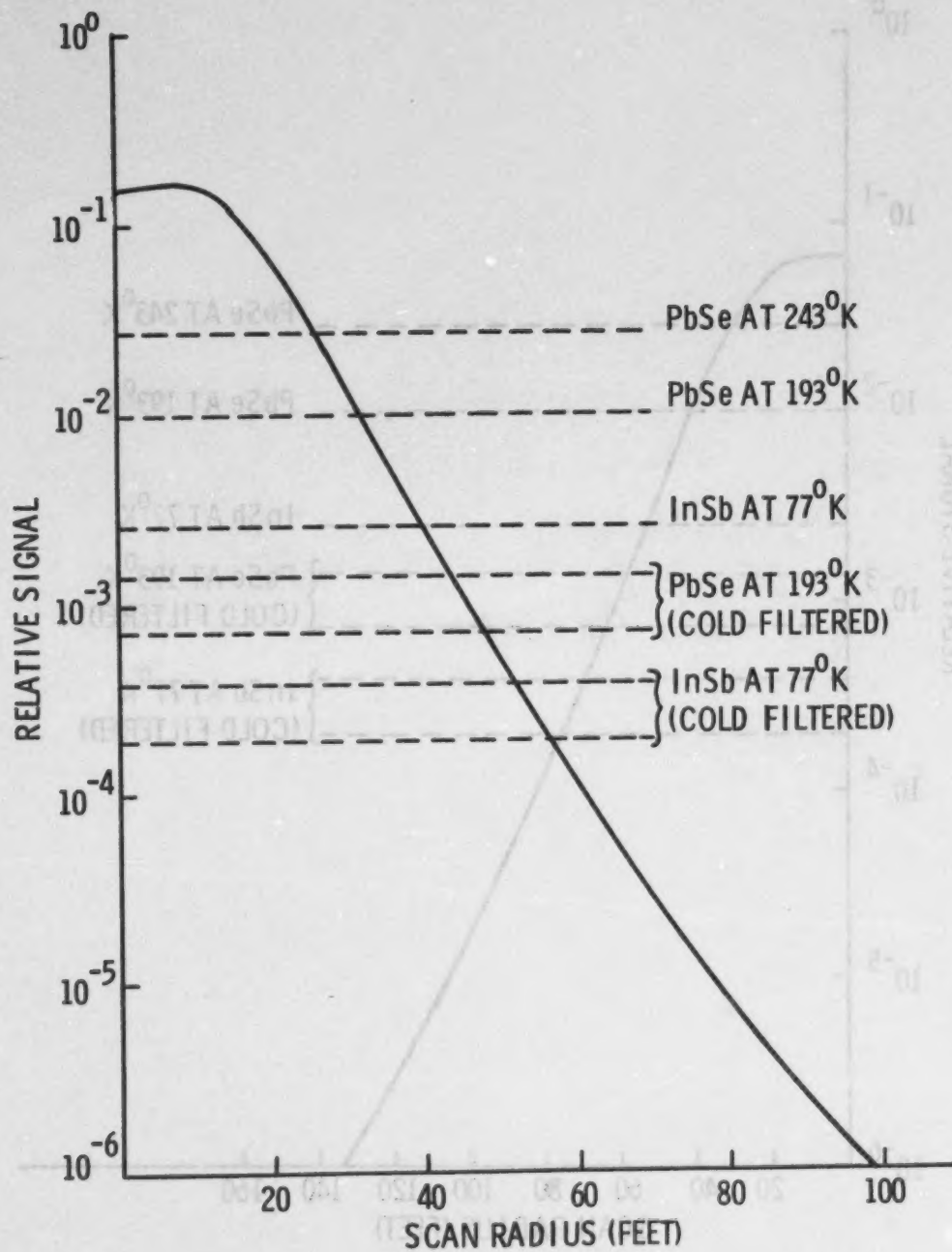


Figure 126. Signal Versus Scan Radius for MOD 2 at 100-Foot Altitude

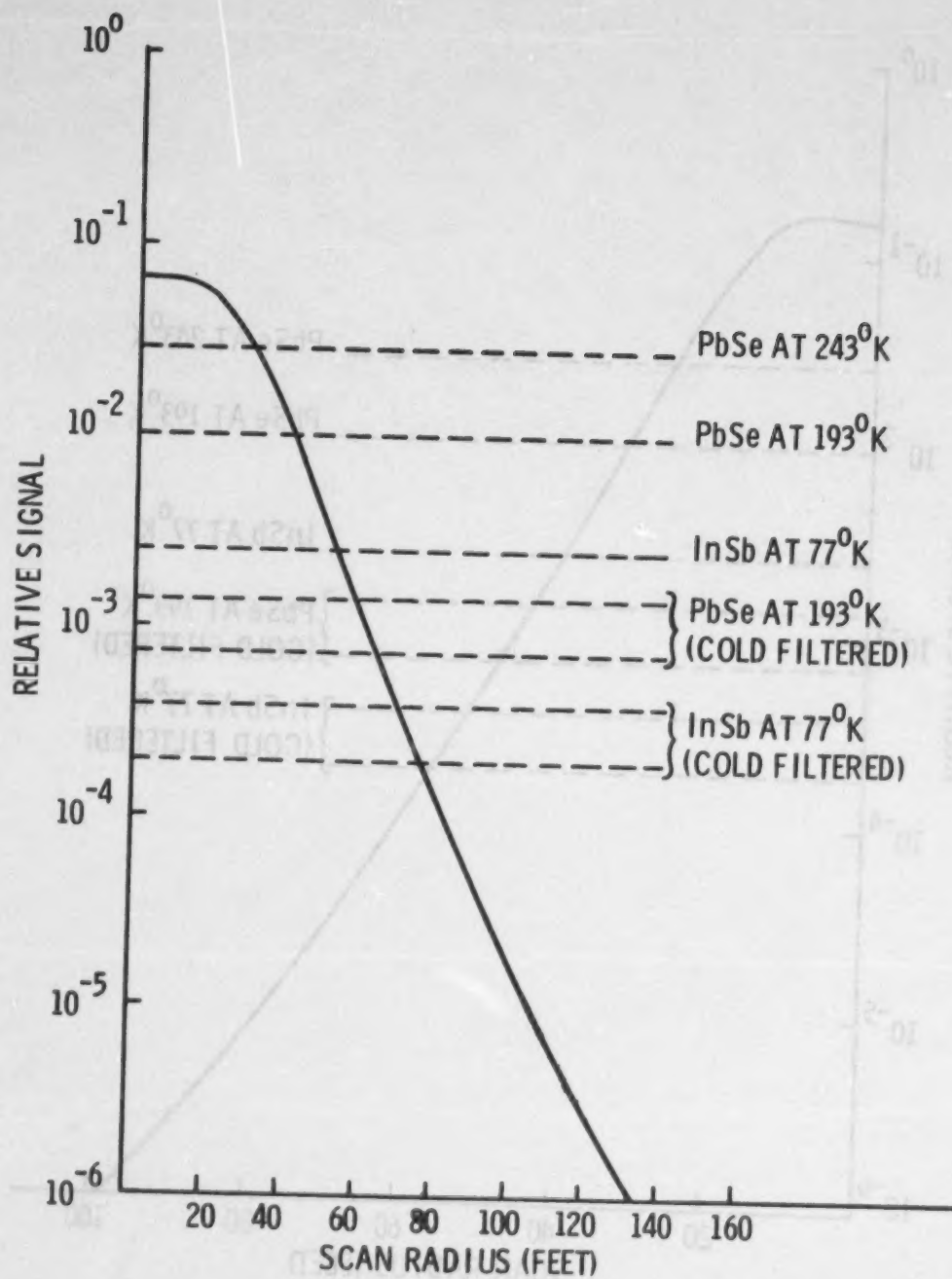


Figure 127. Signal Versus Scan Radius for MOD 2 at 150-Foot Altitude

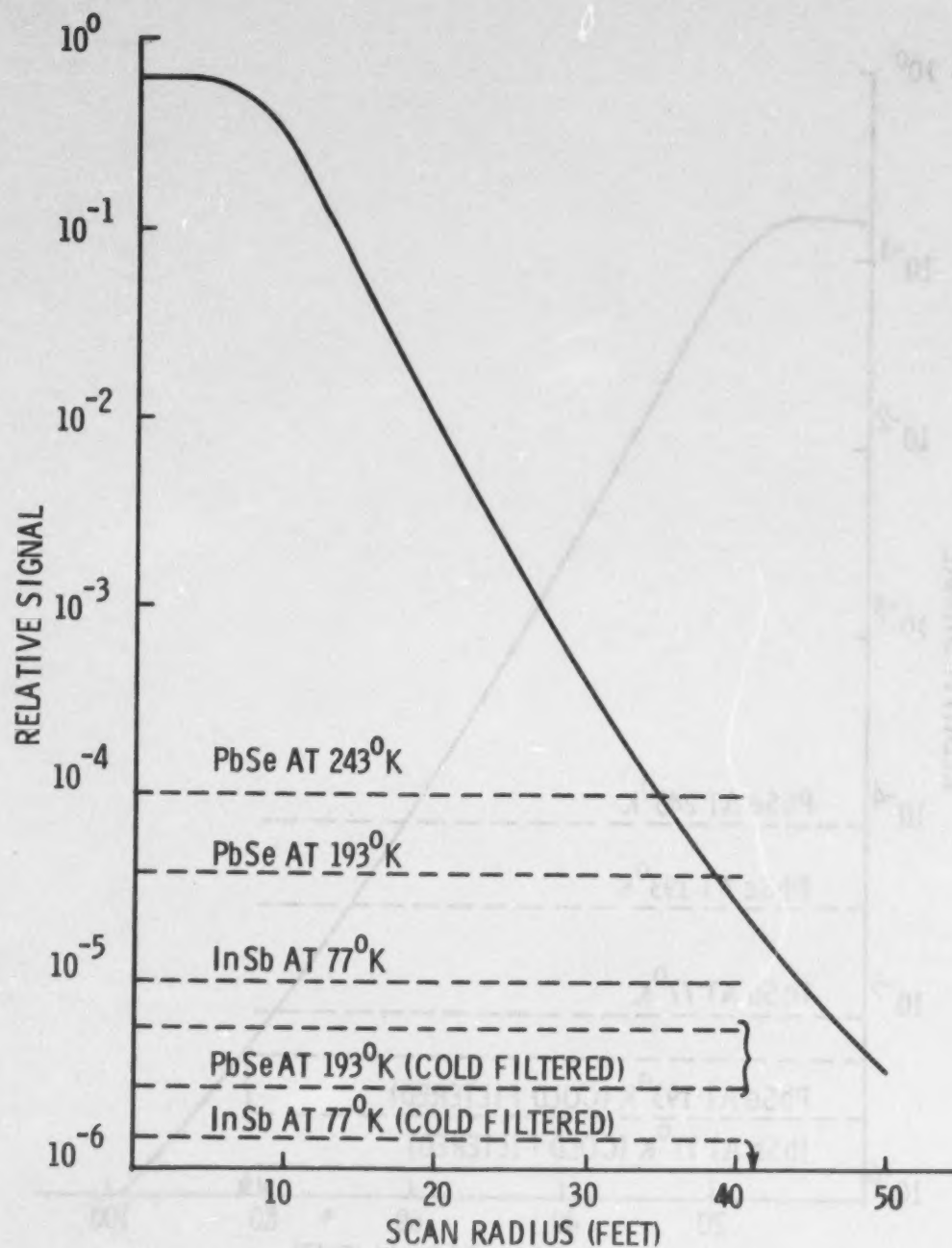


Figure 128. Signal Versus Scan Radius for MOD 3 at 50-Foot Altitude

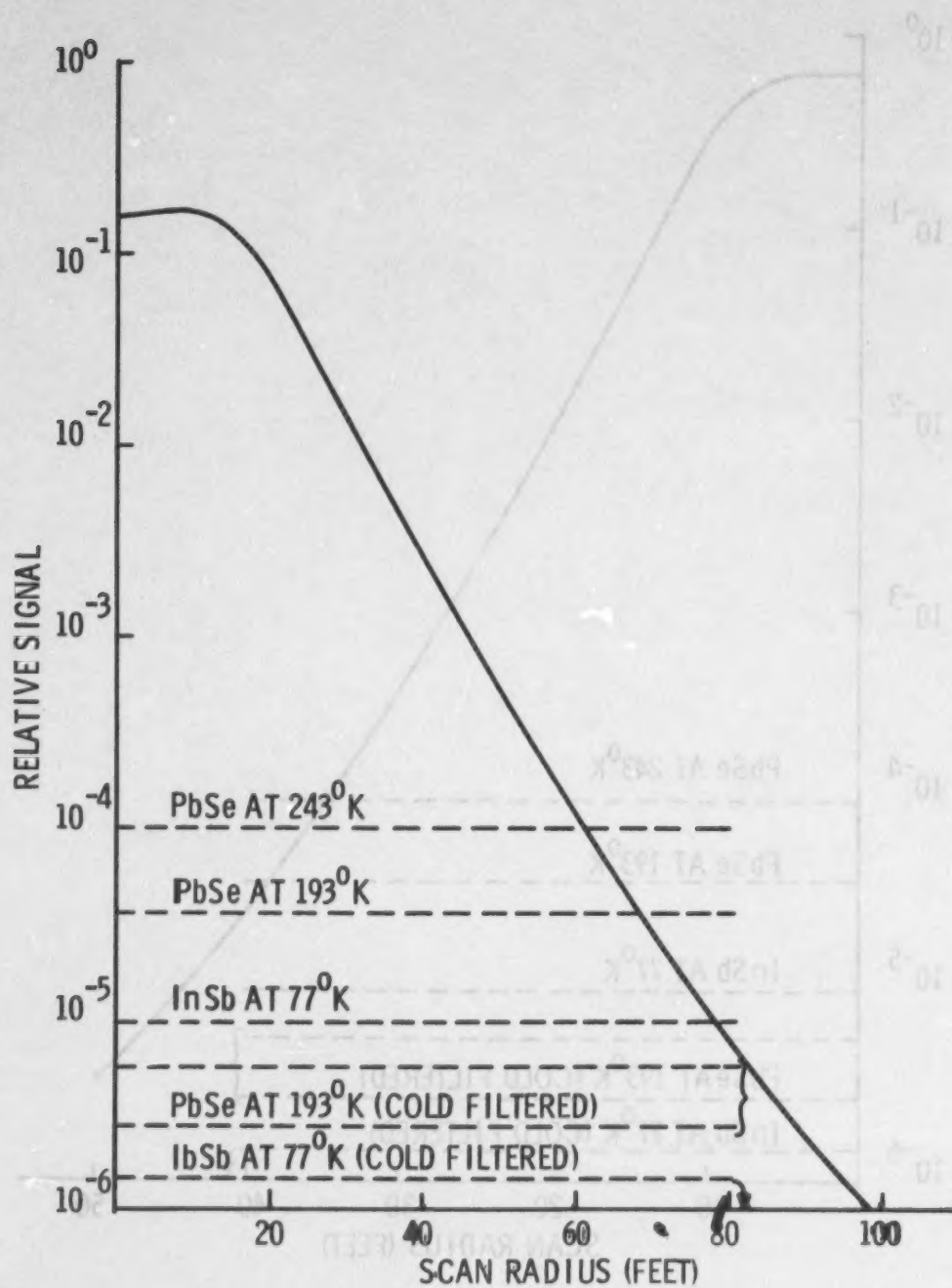


Figure 129. Signal Versus Scan Radius for MOD 3 at 100-Foot Altitude

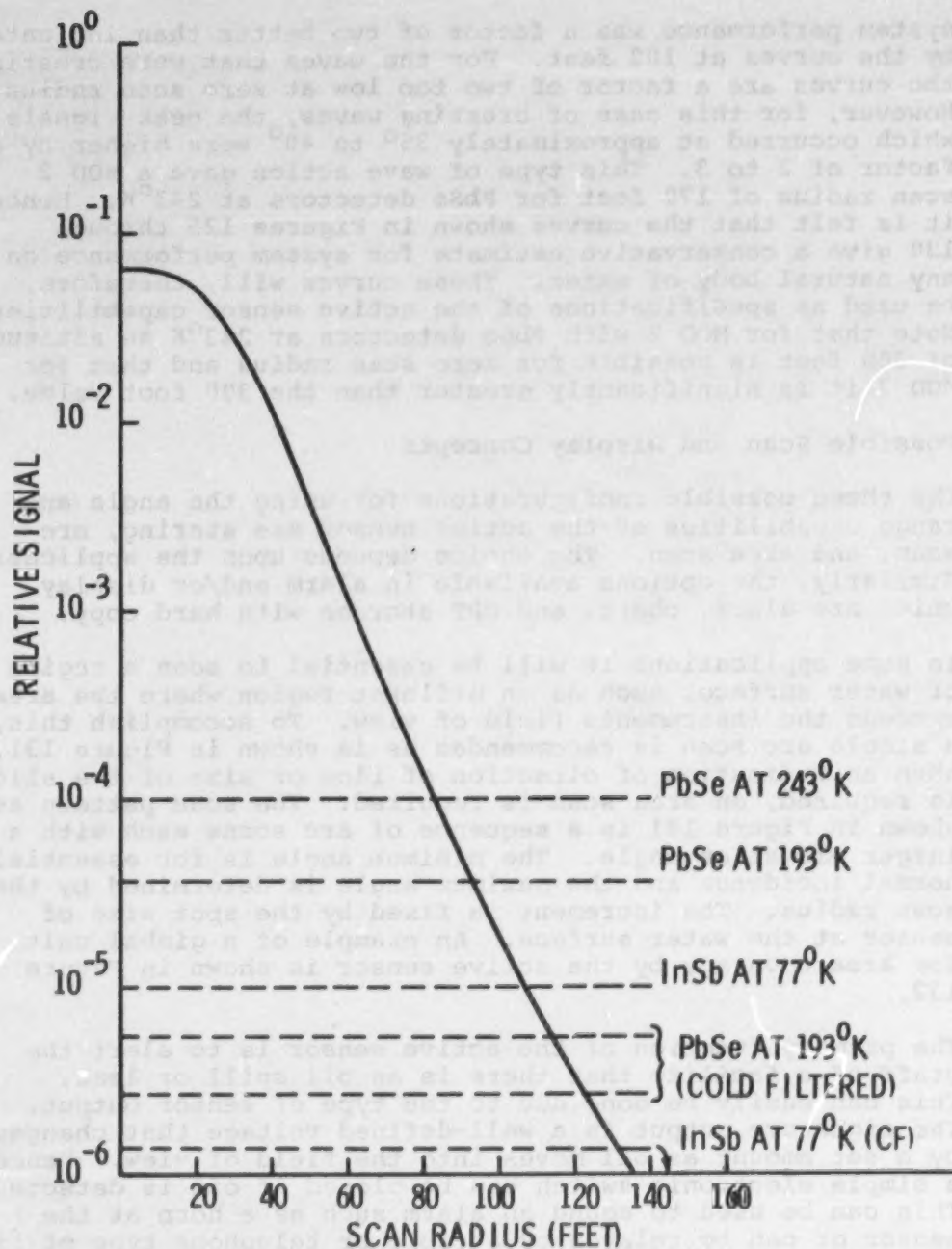


Figure 130. Signal Versus Scan Radius fro MOD 3 at 150-Foot Altitude

system performance was a factor of two better than indicated by the curves at 100 feet. For the waves that were cresting, the curves are a factor of two too low at zero scan radius. However, for this case of cresting waves, the peak signals which occurred at approximately 35° to 40° were higher by a factor of 2 to 3. This type of wave action gave a MOD 2 scan radius of 170 feet for PbSe detectors at 243°K . Hence, it is felt that the curves shown in Figures 125 through 130 give a conservative estimate for system performance on any natural body of water. These curves will, therefore, be used as specifications of the active sensor capabilities. Note that for MOD 2 with PbSe detectors at 243°K an altitude of 300 feet is possible for zero scan radius and that for MOD 3 it is significantly greater than the 300 foot value.

Possible Scan and Display Concepts

The three possible configurations for using the angle and range capabilities of the active sensor are staring, arc scan, and area scan. The choice depends upon the application. Similarly, the options available in alarm and/or display units are alarm, chart, and CRT storage with hard copy.

In some applications it will be essential to scan a region of water surface, such as an effluent region where the area exceeds the instruments field of view. To accomplish this, a simple arc scan is recommended as is shown in Figure 131. When an indication of direction of flow or size of the slick is required, an area scan is required. The scan pattern as shown in Figure 131 is a sequence of arc scans each with a larger elevation angle. The minimum angle is for essentially normal incidence and the maximum angle is determined by the scan radius. The increment is fixed by the spot size of sensor at the water surface. An example of a gimbal unit for area coverage by the active sensor is shown in Figure 132.

The primary function of the active sensor is to alert the staff of a facility that there is an oil spill or leak. This can easily be done due to the type of sensor output. The signature output is a well-defined voltage that changes by a set amount as oil moves into the field of view. Hence, a simple electronic switch can be closed if oil is detected. This can be used to sound an alarm such as a horn at the sensor or can be relayed by a cable or telephone type of line to a central control station. Specific examples are covered in Section XI.

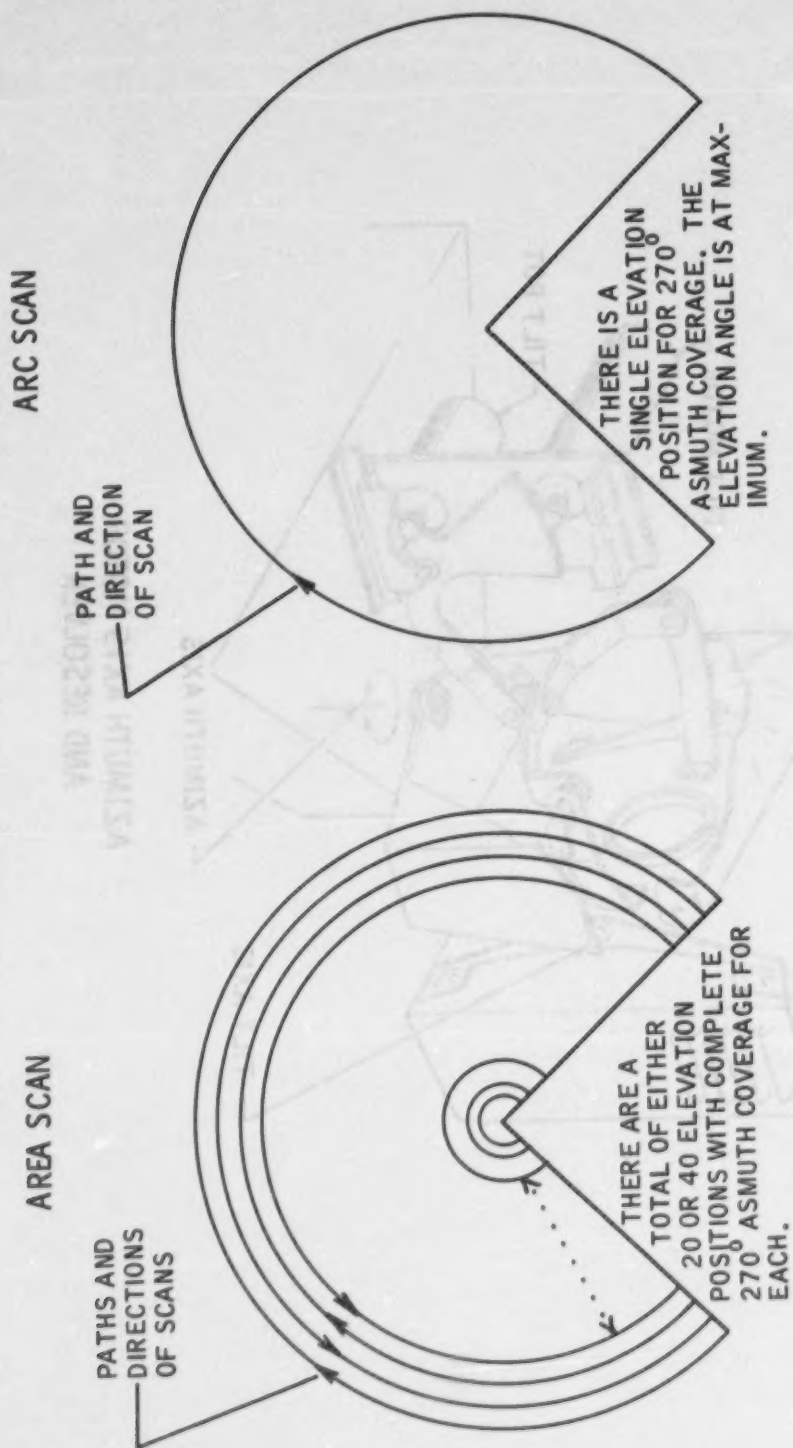
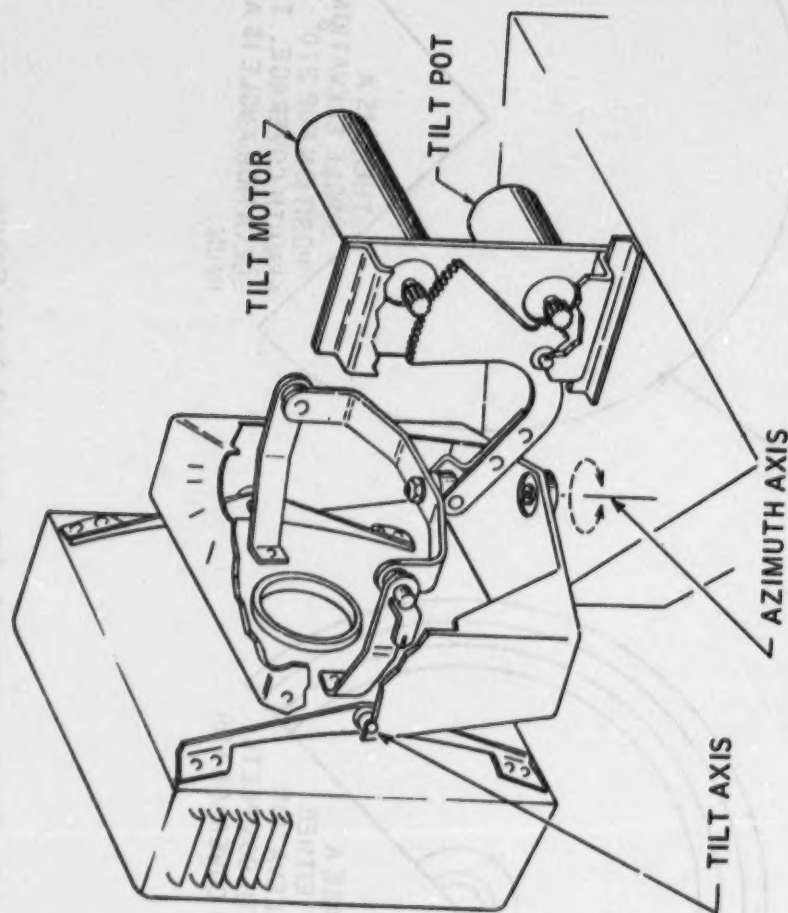


Figure 131. Concept for Arc and Area Scans



AZIMUTH AXIS MOTOR AND RESOLVER

Figure 132. Gimbal System for Active Sensor

Some users of the sensor will need a hard copy of the extent of the spill. For a staring system this will be a 1-inch strip chart with a pen deflection when oil is present. For arc scan coverage the most efficient recording is also a single pen strip chart recorder, while for area scan a storage tube display is required. In both instances an "on" condition indicates the presence of oil. Figure 133 shows the plot circuitry for a 90° area scanner. The resolvers give the angular position of the azimuth scan and convert this to factors related to $\cos \theta$ and $\sin \theta$. The values of E are incremented by the tilt position as indicated by E_N where N is the N th position. The values of $E_N \cos \theta$ and $E_N \sin \theta$ drive the X and Y axis of the display. The oil present condition is indicated by the output of the difference amplifier which drives the display "on" or "off". The resulting display is shown in Figure 134. The heavy lines that appear on the display indicate the presence of oil. The storage tube display can be adapted to provide hard copy on 35 mm film. A record will be taken only if oil is present on the display. A clock annotation will also be recorded on the film.

For an arc scan, the recording can be simplified in the interest of cost, although it will have a distorted representation. A strip chart recorder is recommended with the pen deflection being proportional to the arc. The pen is dropped only when oil is present. If the geometry permits a line scan could be used to prevent this strip chart display from being distorted.

Mean Time Between Failures

The two key factors that effect the maintenance of the active sensor are illuminator usage and the environment. Another minor factor is the detector response.

The optimum operating points for the tungsten halogen lamp and the Xenon flash lamp are described in Section V under transmitter optics. It was determined that the tungsten halogen lamp would operate continuously for 100 days without loss of system reliability. The Xenon flash lamp has a 10^6 pulse rating; hence, the time between failures is determined by the pulse rate, that is, the application of the sensor.

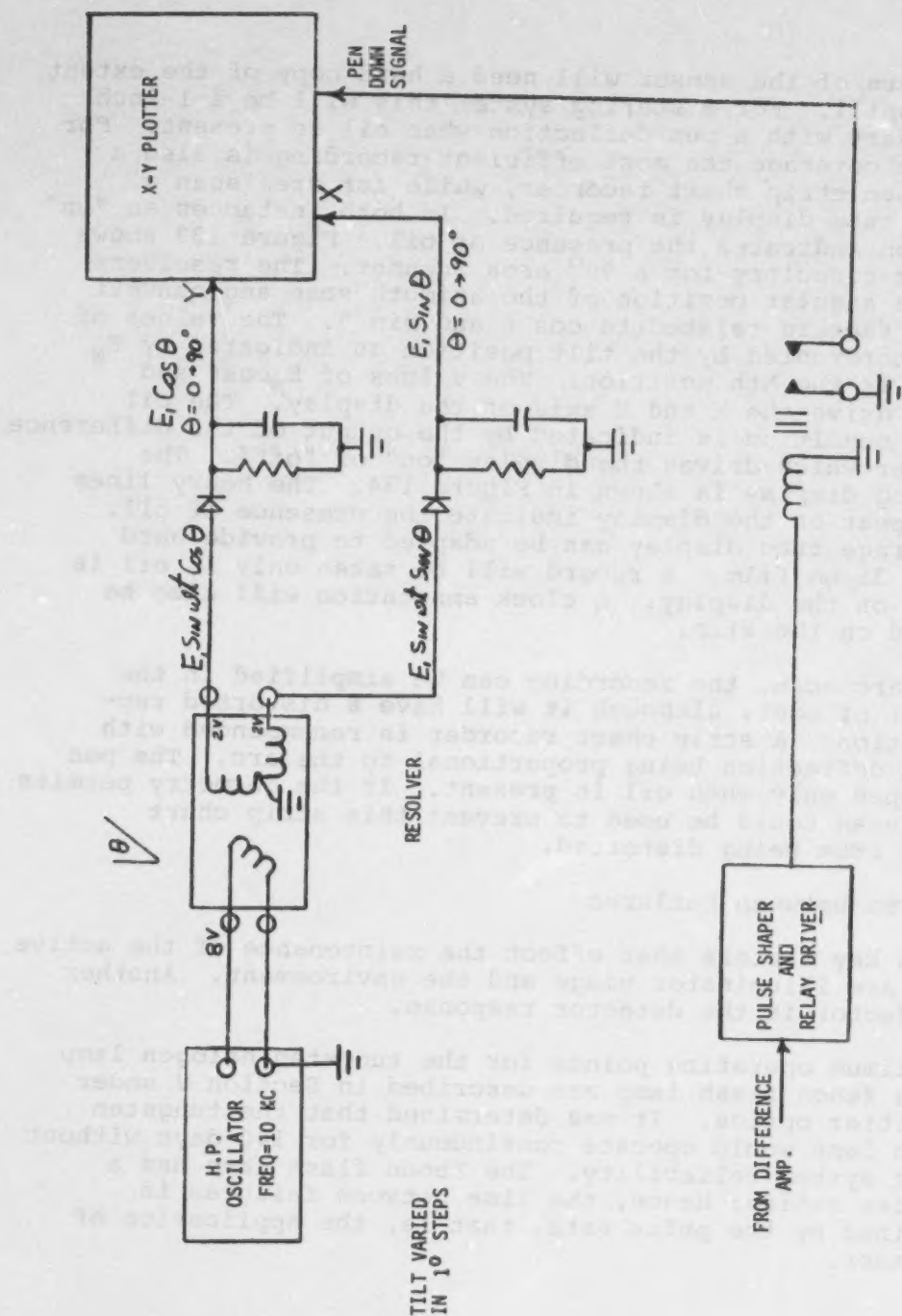


Figure 133. Scanner Block Diagram

SCAN CONCEPT

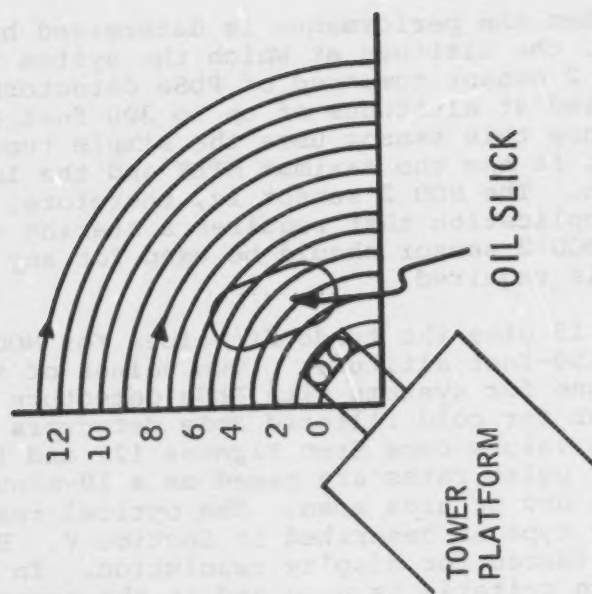
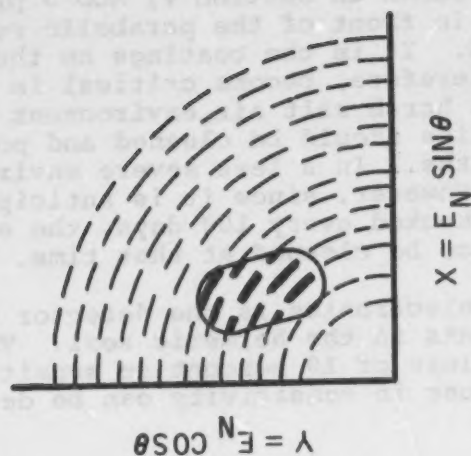


Figure 134. Area Scan Concept and Display

The front surface optics have been set up as refractive elements so that the inside housing can be sealed off from the environment. Though not shown in Section V, MOD 3 production items will have a window in front of the parabolic reflector in the transmitter optics. It is the coatings on the refractive optics which, therefore, become critical in terms of the environment. In a harsh salt air environment the front coatings on the optics should be cleaned and possibly refurbished every six months. In a less severe environment the time is indefinite. However, since it is anticipated that the lamp should be checked every 100 days, the external optical surface should also be cleaned at that time.

The critical item in the electronics is the detector which degrades slowly due to leaks in the hermetic seal. This corresponds roughly to a loss of 10 percent in sensitivity in the first year. The loss in sensitivity can be decreased by improving the vacuum.

Trade-Off Considerations

As discussed in the preceeding paragraphs of this section, there are two factors, simplicity and meantime between failures (MTBF), which must be evaluated relative to system performance. Simplicity when considering mass produced quantities is important in determining the unit cost.

For a staring system the performance is determined by the range required; that is, the altitude at which the system is mounted. The MOD 2 sensor composed of PbSe detectors operating at 243°K can be used at altitudes of up to 300 feet in the staring mode. Since this sensor uses the simple tungsten lamp for a source, it has the maximum MTBF and the lowest cost in production. The MOD 2 sensor is, therefore, optimum for any application that requires a staring sensor. In addition, the MOD 2 sensor should be used for any scan application that is required.

Tables 12 through 15 give the tradeoff values for MOD 2 and MOD 3 sensors at 150-foot altitude. Two values of scan radius are used, one for systems with PbSe detectors at 243°K and the other for cold filtered PbSe detectors at 193°K. The radius values come from Figures 127 and 130. The dwell times or pulse rates are based on a 10-minute frame time whether it is arc or area scan. The optical resolution is fixed by sensor type as described in Section V. However, two cases are considered for display resolution. In the first, the Rayleigh criteria is used and in the second, twice the Rayleigh criteria is used. It is recommended that the value of twice the Rayleigh criteria be used such that the distance between elements equals the size spot.

TABLE 12. MOD 2 COVERAGE TRADEOFF

PbSe DETECTORS AT 243°K

Based Upon (1) 10 Minute Frame Time
 (2) 30 Foot Scan Radius from 150 Foot Altitude
 with 3 Foot Spot Size

Type of Coverage Resolution	Area		Arc	
	Rayleigh (1.5 Ft)	2Rayleigh (3 Ft)	Rayleigh (1.5 Ft)	2Rayleigh (3 Ft)
Number of Resolution Elements	990	260	94	47
Dwell Time (Seconds/Element)	0.68	2.3	6.4	12.8

TABLE 13. MOD 2 COVERAGE TRADEOFF

PbSe DETECTORS COLD FILTERED AT 193°K

Based Upon (1) 10 Minute Frame Time
 (2) 60 Foot Scan Radius From 150 Foot Altitude
 with 3 Foot Spot Size

Type of Coverage Resolution	Area		Arc	
	Rayleigh (1.5 Ft)	2Rayleigh (3 Ft)	Rayleigh (1.5 Ft)	2Rayleigh (3 Ft)
Number of Resolution Elements	3860	990	189	94
Dwell Time (Seconds/Element)	0.16*	0.6	3.2	6.4

*Unattainable

TABLE 14. MOD 3 COVERAGE TRADEOFF

PbSe DETECTORS AT 243°K

Based Upon (1) 10 Minute Frame Time
 (2) 10^6 Pulses From the Lamp
 (3) 83 Foot Scan Radius From 150 Foot Altitude
 with 6 Foot Spot Size

Type of Coverage Resolution	Area		Arc	
	Rayleigh (3 Ft)	2Rayleigh (6 Ft)	Rayleigh (3 Ft)	2 Rayleigh (6 Ft)
Number of Resolution Elements	1910	490	130	65
Number of Frames per Lamp	520	2020	7690	15380
Number of Days Per Lamp	3.6	14.1	53.4	107
Pulse Rate (Pulses per Second)	3.2*	0.8	0.9	1.0

*Marginal Performance

TABLE 15. MOD 3 COVERAGE TRADEOFF

PbSe DETECTORS COLD FILTERED AT 193°K

Based Upon (1) 10 Minute Frame Time
 (2) 10^6 Pulses From the Lamp
 (3) 110 Foot Scan Radius From 150 Foot Altitude
 with 6 Foot Spot Size

Type of Coverage Resolution	Area		Arc	
	Rayleigh (3 Ft)	2Rayleigh (6 Ft)	Rayleigh (3 Ft)	2Rayleigh (6 Ft)
Number of Resolution Elements	3226	806	173	86
Number of Frames Per Lamp	310	1241	5780	11628
Number of Days Per Lamp	2.2	8.6	40.1	80.8
Pulse Rate (Pulses per Second)	5.4	1.3	0.3	0.15

*Marginal Performance

It should be noted that for those cases where the dwell time is longer than one second, the signal-to-noise ratio could be increased by the square root of the magnitude dwell time. However, this is a second order effect in the size of the scan radius due to the strong dependence on wave action at the larger radius values. For example, the most extreme case is a factor of 12.8-second dwell time. This occurs for MOD 2 in an arc scan mode. The signal-to-noise ratio could be increased by a factor of 3.5 which would increase the scan radius from 30 feet to 40 feet. For all other examples, the change is significantly less and, hence, has been ignored in the tables.

The other way that the dwell time could be interpreted is that the frame time of 10 minutes could be decreased by the ratio of 1 second to the dwell time. Again, for the MOD 2 case with the 12.8-second dwell time, the frame time could be decreased to 0.8 minutes and still have a 30-foot scan radius. The possible applications are discussed in Section XI.

SECTION X

SYSTEM CONCEPTS, PASSIVE SENSOR

Introduction

Analysis of data collected during the demonstration phase of the Oil Spill study program has helped establish the criteria for development of system concepts. Thermal properties of oil on a water surface have been recorded for a variety of environmental and oil film conditions. Several oil types were investigated as well as various volumes. The primary conclusion drawn from the test program is that under most conditions, oil causes a thermal anomaly on water surfaces; thus, the thermal infrared portion of the electro-magnetic spectrum offers excellent opportunities for detection and surveillance. Probably the greatest advantage that thermal infrared offers is the ability to utilize a passive sensor and work in total darkness under most weather conditions.

Texas Instruments approach to the problem of defining system concepts, based on the results of the test phase, has been twofold. The first approach was to optimize infrared (IR) detection techniques. The second approach was to define, based on the applications, the system configuration best suited to solving the problem for all the various locations and situations. The Multipurpose Infrared System (MIRS), developed by Texas Instruments and used in the demonstration phase of this program has proven that it can provide useful real-time imagery of oil-to-water thermal contrast. However, the Texas Instruments approach was not to necessarily develop concepts centered around this sensor. The problem has been evaluated objectively to arrive at the optimum system concept.

The first goal, optimization of IR detection techniques, refers to basic system concepts. The primary objective here was to determine the spectral band to be used, which determines the detector type, which in turn dictates the cryogenic requirements.

Recent research by individuals, in addition to that work done by Texas Instruments during the test phase of this program, indicates that thermal IR offers the most potential for imaging of oil spills on water surfaces. Polcyn and Wezernak in a report entitled Technological Assessment of Remote Sensing Systems for Water Pollution Control-Oil Pollution reported that "The ultraviolet, red, near infrared, and the 8 to 14 micron infrared appear to provide the optimum regions for oil pollution detection." They further state "Radar, microwave

radiometry, and the 8 to 14 micron infrared techniques are unaffected by hours of darkness; and hence offer a 24 hour detection capability. Radar and microwave will be affected by sea-state and thus of doubtful use for monitoring under calm water conditions." The system described in this section utilizes the thermal properties of oil as the detection and surveillance mechanism.

The many and varied possible applications (i.e., rivers, harbors, estuaries, etc.) located on towers, bridges, buoys, loading docks, offshore oil platforms, and others have dictated the requirement for the second goal. That goal was to define the specific system configuration best suited and most versatile for the solution of the oil spill surveillance problem.

The key to attaining this goal was applications of the sensor. The principles of operation and components of this sensor had to be such that it could be adapted to the various situations requiring water surface monitoring. A discussion of how the sensor can be applied to various situations is in Section XI.

The fixed, platform-mounted imaging sensor described in this section does not propose to positively identify oil spills as to type or thickness. It is proposed to complement the active oil detection sensor where applicable or stand alone where necessary. Texas Instruments feels the approach taken will provide the most versatile and economical source of imagery of oil on inland and coastal waterways.

System Description

The system conceived to fulfill the requirements of this program is a single-channel line-scanning device as opposed to the multichannel framing sensor used for the demonstration phase. The line scan approach was chosen to permit versatility in adapting the system to different applications. A stationary sensor continuously scanning one line at a time to detect the presence of oil can be used across rivers and canals, downstream from loading docks, or possibly mounted on a ship as illustrated in Figure 135. To monitor a small bay or inlet, an area sector scan could be employed. This can be accomplished using the same sensor scanning from vertical radially outward. The desired azimuth angle can be attained using a gimbal system. This configuration would cover a full 360 degrees if desired for an application such as an offshore oil platform. Figure 136 shows the area coverage capability of this technique.

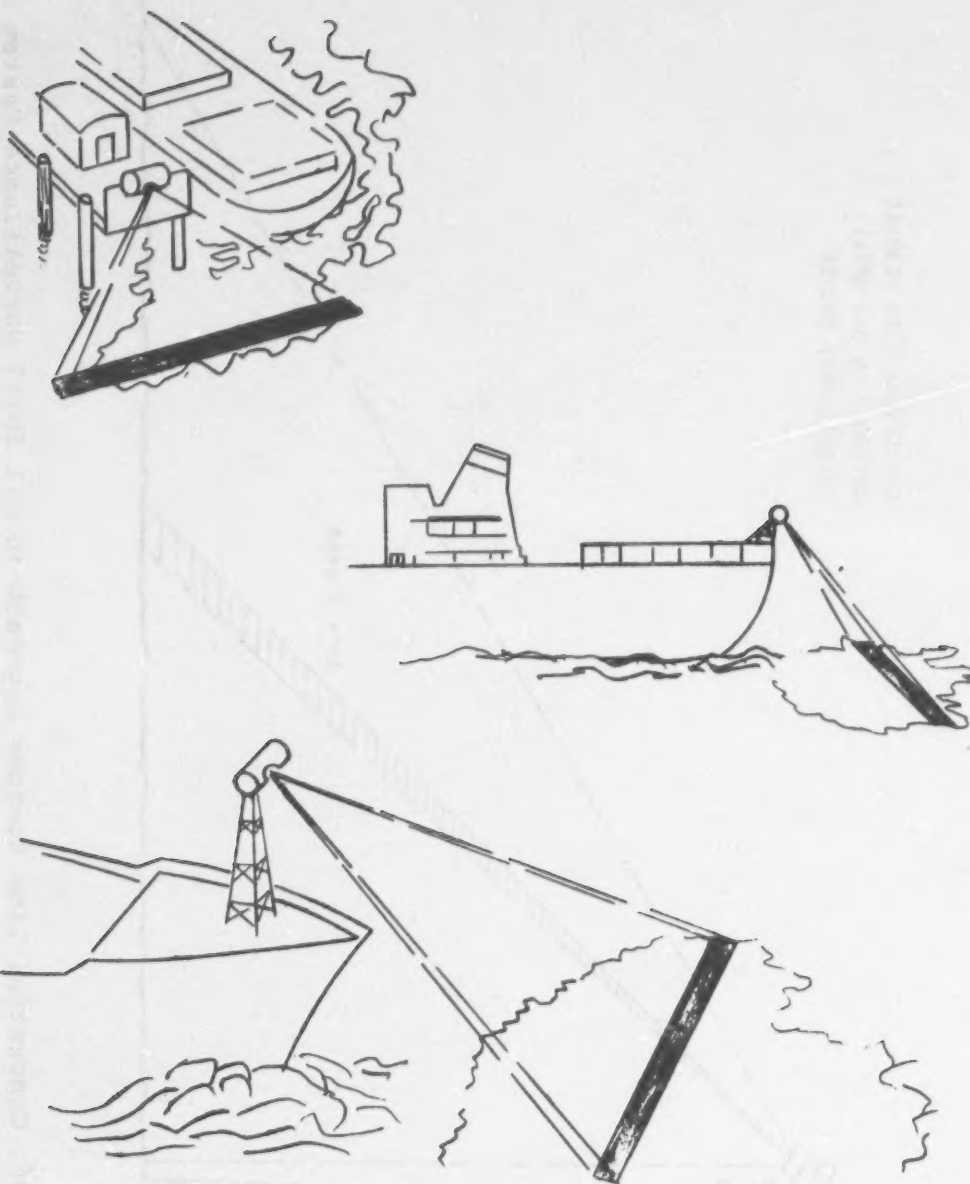


Figure 135. Shipboard Application of Passive Scanner

CONCEPTUAL LINE SCANNER
APPROACH TO OIL SPILL
SURVEILLANCE SYSTEM

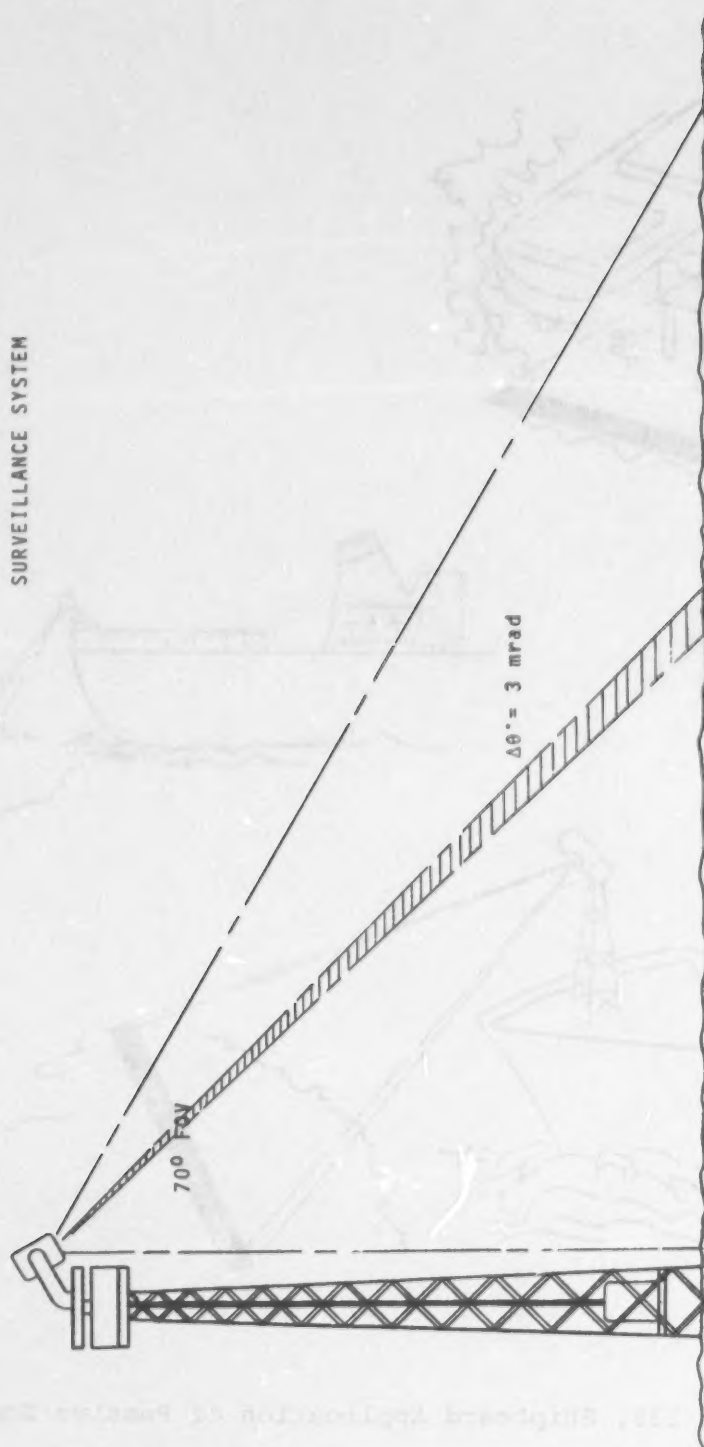


Figure 136. Conceptual Line Scanner Approach to Oil Spill Surveillance System

The scanner is conceived to be a variation of the RS-18, an airborne IR line scanner built by Texas Instruments. The RS-18 is intended for external mounting on aircraft and is therefore aerodynamically designed. This, of course, would not be a requirement for mounting the sensor on a fixed platform, but a mechanical reconfiguration of the sensor would produce an applicable system. Outline drawings of the RS-18 are shown in Figure 137.

The scanner utilizes a single-sided wedge scan mirror with a cassegramian optical system. Additional parameters of the existing RS-18 are listed in Table 16. The scan mirror is rotated by a variable-speed dc motor. Scan rates from 100 scans per second down to a few scans per second are possible to provide the best presentation for the particular application.

This system with a 3-milliradian resolution capability will provide contiguous coverage of a 360-degree area with a frame time of 21 seconds if operating at 6000 rpm (100 scans per second). A multichannel framing system with a 10 by 5 degree field of view would require external scanning in both azimuth and elevation and would require a longer time to cover the same area. Additionally, the entire area being surveyed may be continuously monitored in real-time using a storage tube display system. Other advantages of this approach over the multichannel imaging system are:

- (1) Simplicity - single channel
- (2) Bandwidth - 100 kHz maximum
- (3) Ease of calibration
- (4) Low cost
- (5) Reliability
- (6) Continuous areal coverage
- (7) Single axis external scan, azimuth
- (8) Declassified status
- (9) Versatility

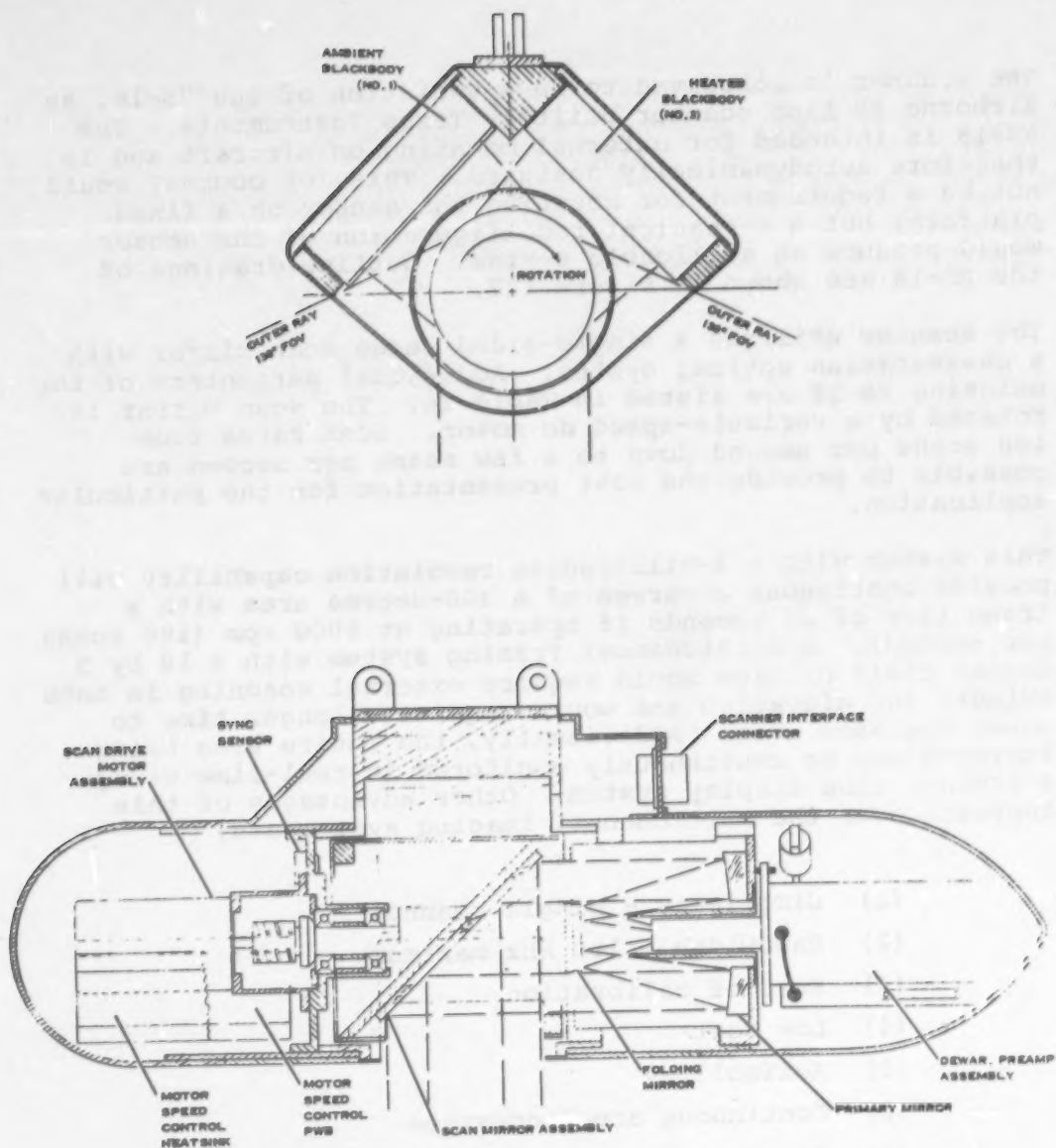


Figure 137. RS-18 Outline Dimensions

TABLE 16. RS-18 SPECIFICATIONS

Scan speed	5000 rpm
V/H	0.015 to 012
IFOV	2.5 mrad
Field of view	100 degrees
Roll compensation	+ 15 degrees
Roll rate for 1-mrad perturbation	17 degrees/second minimum
detectors	1-HgCdTe (cooled) 1-InSb (cooled) 1-Silicon (uncooled)
Cooling type	Dewar
Hold time	6 hours, typical
Aperture	7.7 inches ²
Focal length	6 inches
Power required	Less than 7.4 amperes at 28 Vdc
Calibration Sources	1-ambient 1-heated

The field of view of the scanner can also be made variable to adapt it to various conditions. This can be accomplished by maintaining the full 100-degree field of view design of the system and electronically reducing the field of view of the output signal to any value desired.

In choosing detector material, the two primary tradeoff considerations were sensitivity to oil and the logistics problems encountered in cooling the detector with liquid nitrogen on a remote platform.

Atmospheric transmission of IR energy is greatest in the 3 to 5 micron region and the 8 to 14 micron region of the electromagnetic spectrum. Thus, a choice of detector materials sensitive in one or both of these regions is recommended. Lead selenide (PbSe) is sensitive in the 3 to 5 micron region and mercury-cadmium-telluride (HgCdTe) is sensitive in the 8 to 14 micron region.

60382

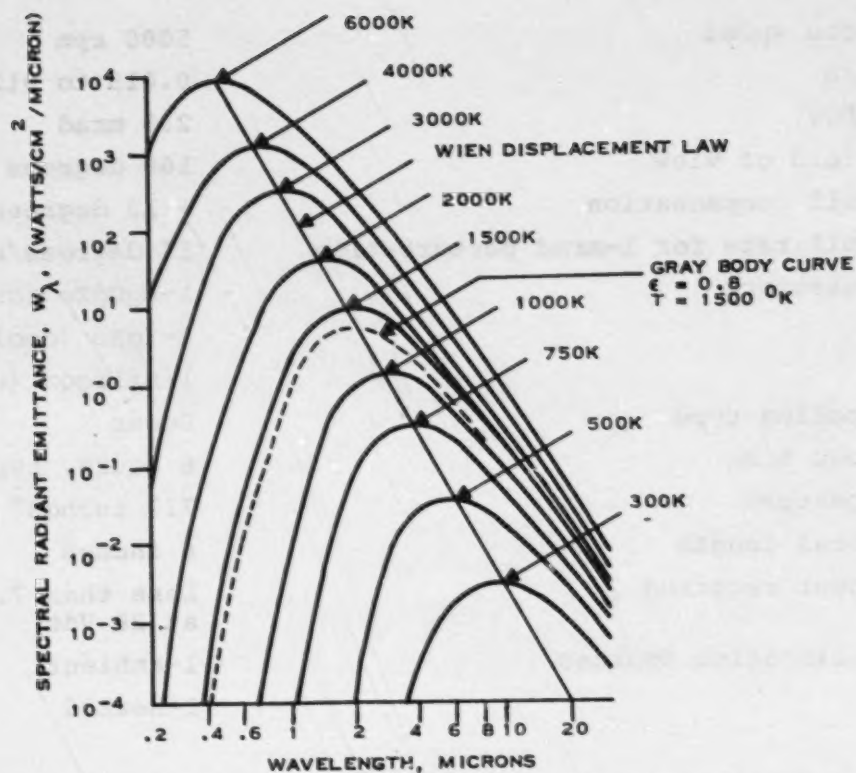


Figure 138. Spectral Radiant Emittance Curves for Blackbodies at Several Absolute Temperatures

In choosing between these two materials, one must first choose which consideration is more important. According to Wein's Displacement Law, the wavelength (λ) for maximum emission of energy from a black body is a function of its ambient temperature as described by

$$\lambda_{\max} T = 2900 \quad (1)$$

where $\lambda_{\max}$ is in microns and T is in degrees Kelvin. This relationship is presented graphically in Figure 139. This graph shows that much less emissivity is available in the 3 to 5 micron region than in the 8 to 14 micron region for ambient temperatures at about 300°K. Thus, if sensitivity is the primary consideration, even over logistics problems, HgCdTe is the logical choice.

For effective sensitivity to targets at ambient temperature, it is necessary to cool HgCdTe to 77°K, which is accomplished with a liquid nitrogen cooler. The following paragraphs describe the cooling requirements.

Cooling Requirements

The following paragraphs describe a conceptual design that is compatible with the thermal requirements of cooling a single element HgCdTe detector operating at 77°K that does not require a closed cycle cooler nor a frequent supply of a liquid coolant such as liquid nitrogen. (The word "frequent" is also discussed in more detail.)

In order to avoid the use of a closed-cycle cooler, a liquid transfer system is proposed. The only way that a liquid transfer system will be practical will be to have a large volume of liquid nitrogen placed on the tower itself. An earlier study indicated that the losses for a 100 foot vacuum insulated transfer line from a ground storage vessel would be too large (22 watts) to make this a practical alternative.

After consideration of a number of geometrical arrangements, it is suggested that the detector/optics/electronics housing be mounted on top of the storage vessel or on a platform just above the vessel. Figure 140 shows how this arrangement will allow an unrestricted 360 degree field of view for the detector and keep the supply of liquid nitrogen close to the detector to be cooled.

Sensor/Optics Rotates
Full 360° and Reverses.
Rate of Rotation 90°/Min.

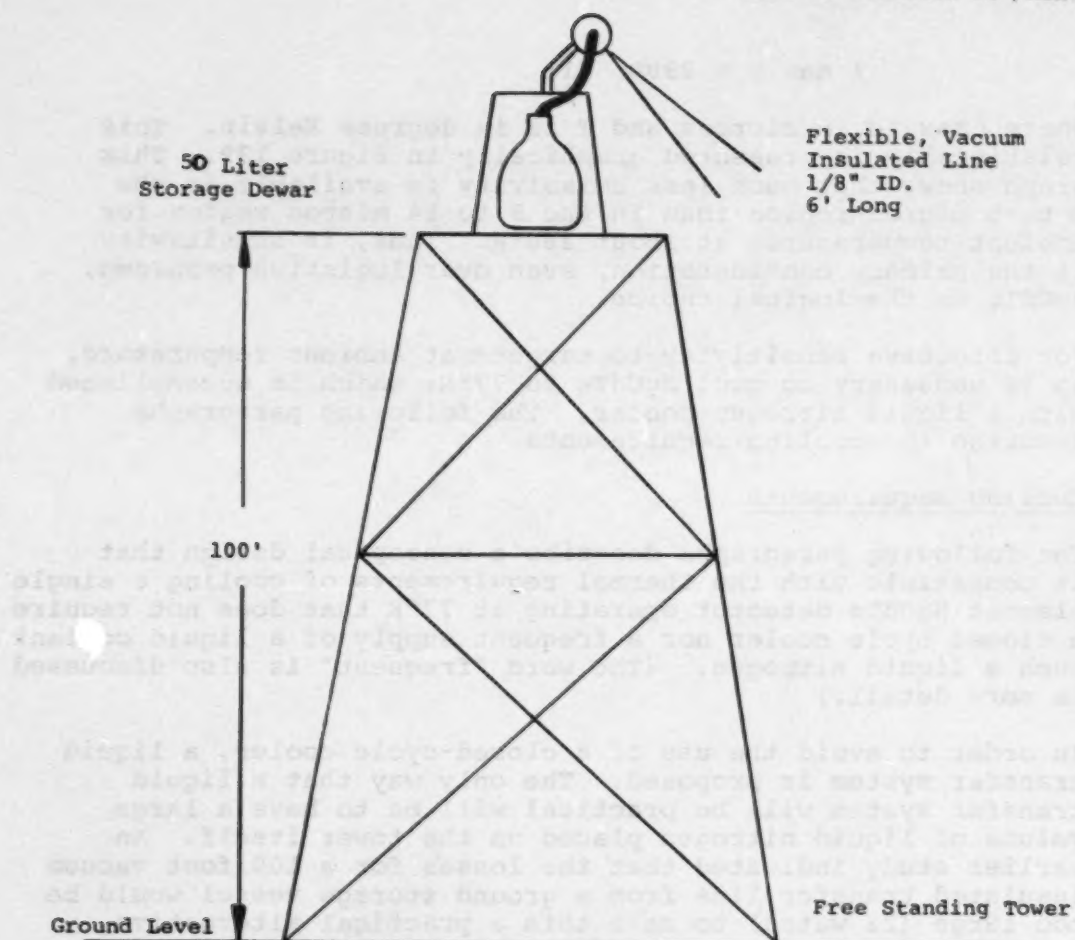


Figure 139. Liquid Transfer System and Passive Sensor Mounted on Tower

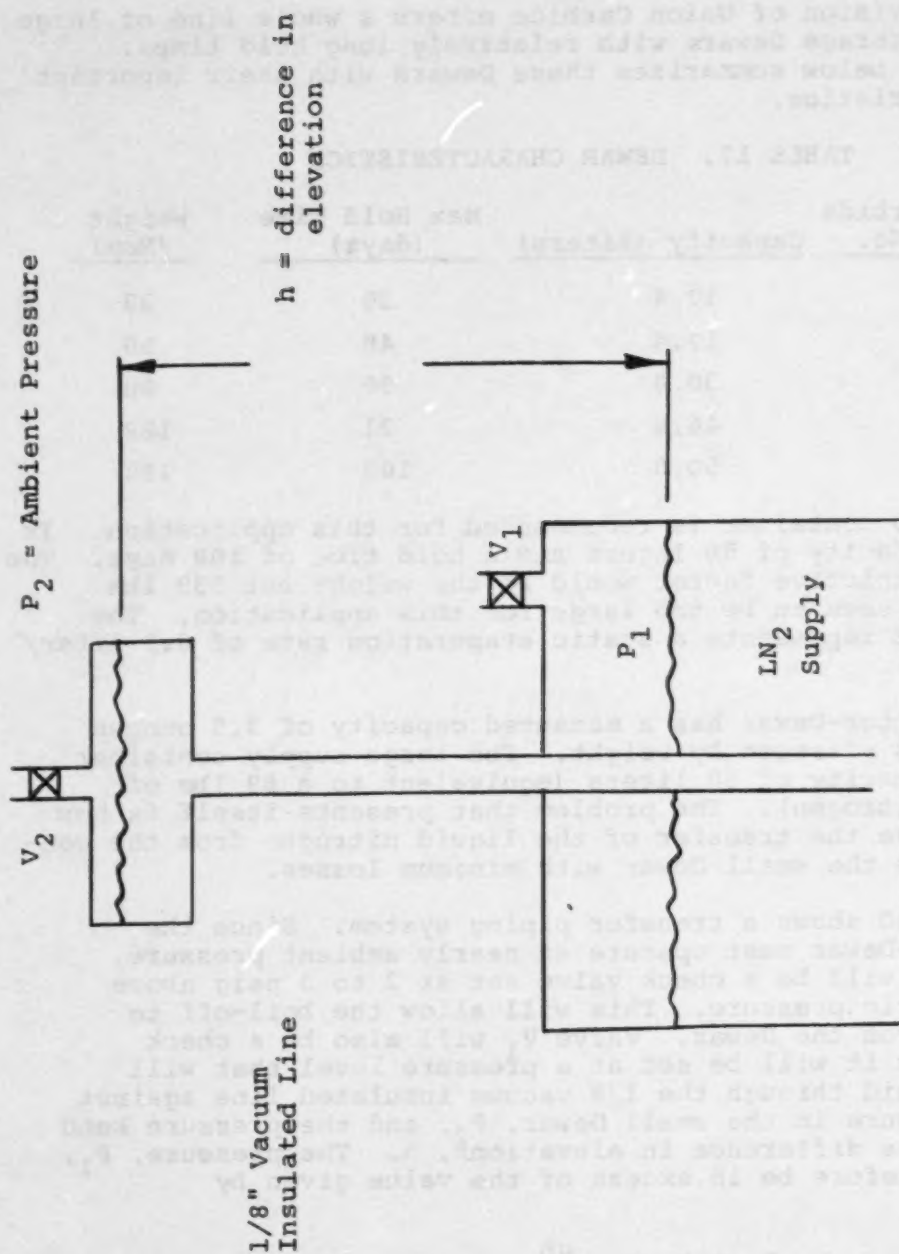


Figure 140. Transfer Piping System

Linde Division of Union Carbide offers a whole line of large volume storage Dewars with relatively long hold times. Table 17 below summarizes these Dewars with their important characteristics.

TABLE 17. DEWAR CHARACTERISTICS

Union Carbide Catalog No.	Capacity (liters)	Max Hold Time (days)	Weight (Nom)
LR-10	10.4	30	33
LR-17	17.4	48	50
LR-31	30.0	90	88
LR-40	46.6	21	128
LR-50	50.0	100	130

The LR-50 container is recommended for this application. It has a capacity of 50 liters and a hold time of 100 days. The only restrictive factor would be the weight but 130 lbm does not seem to be too large for this application. The hold time represents a static evaporation rate of 0.5 liter/day.

The detector-Dewar has a measured capacity of 3.5 ounces of liquid nitrogen by weight. The large supply container has a capacity of 50 liters (equivalent to a 89 lbm of liquid nitrogen). The problem that presents itself is how to achieve the transfer of the liquid nitrogen from the container to the small Dewar with minimum losses.

Figure 140 shows a transfer piping system. Since the detector-Dewar must operate at nearly ambient pressure, valve V_2 will be a check valve set at 2 to 3 psig above atmospheric pressure. This will allow the boil-off to escape from the Dewar. Valve V_1 will also be a check valve but it will be set at a pressure level that will force fluid through the 1/8 vacuum insulated line against the pressure in the small Dewar, P_2 , and the pressure head due to the difference in elevations, h . The pressure, P_1 , must therefore be in excess of the value given by

$$P_1 \geq P_2 + \frac{gh}{g_c}$$

where

$$\text{LN}_2 = 50.61 \text{ lbm/ft}^3$$

$$g = 32.2 \text{ ft/sec}^2$$

$$g_c = 32.2 \text{ lbm ft/sec}^2 \text{ lb}$$

$$h = \text{elevation in. ft}$$

$$p = \text{pressure in. lb}_f/\text{ft}^2$$

The resultant equation becomes

$$P_1 \geq P_2 + (50.61)h$$

Once the exact geometry is set, the check valve may be selected that will control the pressure, P_1 , to the extent that it will be great enough to accomplish the fluid transfer. For purposes of this discussion, the pressure drop due to the small amount of liquid nitrogen through the 0.125 inch inside dimension (ID) line has been ignored.

This proposed transfer system is extremely simple in that it requires no level sensors, no solenoid valves, no sequencing operations and as will be demonstrated in the next section, a minimum heat input to the system.

The frequency at which the 50 liter container must be refilled depends on four factors:

- (1) Heat load requirements of the detector-Dewar assembly.
- (2) Losses in the vacuum insulated transfer line.
- (3) Static evaporation rates from the 50 liter container itself.
- (4) Effect of variable ambient temperature.

These four factors will be discussed independently.

Heat Load Requirements of the Detector Assembly

The total heat load requirements for a single element HgCdTe detector are determined through calculation of the following quantities:

- (1) Heat generation in the detector due to the resistance of the detector and the bias power at

- (2) Conduction of energy through the detector leads.
- (3) Radiant heat load on the detector from the window and the surrounding vacuum enclosure and lead tube.
- (4) Joulean heating in the detector leads.

There are some experimental data regarding this particular system that has been used in the RS-18 system. In that case, the small Dewar had to be refilled every 6 hours. It is estimated that approximately 75 percent of the liquid had been evaporated at that time. The full 3.5 ounces capacity is equivalent to 0.218 lbm. The 75 percent usage factor yields a mass of approximately 0.150 lbm. Using this mass and a time of 6 hours the usage rate becomes

$$\text{usage rate} = \dot{m} = \frac{0.150 \text{ lbm}}{6 \text{ Hr}} = 0.025 \text{ lbm/Hr}$$

This represents a heat load of

$$q = \dot{m} h_{fg}$$

$$q = (0.025 \frac{\text{lbm}}{\text{Hr}}) (85.32 \text{ Btu}) (1 \text{ watt}/3.41 \text{ Btu/Hr})$$

$$q = 0.625 \text{ watts}$$

This is a reasonable heat load estimate for the detector.

Heat losses in the Vacuum Insulated Transfer Line

The vacuum insulated line (flexible) suggested for this application is manufactured by Hofman Division of Minnesota Valley Engineering Incorporated. For the small flow rates involved the 1/8 inch nominal hose size line is recommended.

$$\text{ID} = 0.125 \text{ inches}$$

$$\text{OD} = 2.25 \text{ inches}$$

Assuming that a length of 6 feet is required to allow for the rotation of the optical scanner housing, the heat loss is

$$q = (0.3 \text{ Btu/hr ft}) (6 \text{ ft})$$

$$= 1.8 \text{ Btu/hr} \frac{1 \text{ watt}}{3.41 \text{ Btu/hr}}$$

$$q = 0.53 \text{ watt}$$

This represents a loss in mass of

$$\dot{m} = \frac{q}{h_{fg}} = \frac{1.8 \text{ Btu/hr}}{85.32 \text{ Btu/lbm}} = 0.021 \frac{\text{lbm}}{\text{Hr}}$$

Static Evaporation From the Large Container

The product bulletin regarding the 50 liter Linde container indicates that the static evaporation rate is 0.5 liters/day. The density of liquid nitrogen is 1.77 lbm/liter resulting in a loss given by:

$$\dot{m} = 0.037 \frac{\text{lbm}}{\text{hr}}$$

The total loss in mass due to all sources of heat input is therefore given by:

$$m \text{ (vacuum insulated line)} = 0.021$$

$$m \text{ (static tank evaporation)} = 0.037$$

$$m \text{ (detector heat load)} = 0.025$$

$$m_{\text{Total}} = 0.083 \text{ lbm/hr}$$

The total capacity of the 50 liter tank is 89 lbm of liquid nitrogen. It is therefore estimated that it will last for a period of time given by:

$$\text{Time} = \frac{89 \text{ lbm}}{0.083 \text{ lbm/hr}} = 45 \text{ days}$$

It is therefore concluded that every month to a month and a half the large container will have to be refilled.

Effect of Variable Ambient Temperature

The static evaporation rate of 0.5 liters/day used previously is for an ambient temperature of 70°F. It is obvious that the application requiring the placement of the container on top of a tower will expose the system to greater losses. Discussions with representatives from Linde Division of Union Carbide reveal no insight into the problem; it was indicated that they felt the increase to be rather small.

In order to make an estimate of the change in ambient heat load, it is necessary to determine the temperature of the outside surface of the vessel. This will be the radiation equilibrium temperature. It may be determined by equating the solar heat load on the vessel to the heat lost by convection to the ambient air and by radiation exchange with its surroundings.

$$q_{\text{solar}} = q_{\text{conv}} + q_{\text{rad}}.$$

(1) Solar Heat Load: The solar constant is 442 Btu/hr ft². Assuming that the transmissivity of the atmosphere is equal to 0.8, the irradiation on the surface of the vessel is given by

$$\begin{aligned} G_i &= \tau G_o \\ &= (0.442 \text{ BTU/hr ft}^2)(0.8) \\ &= 353.6 \text{ BTU/hr ft}^2 \end{aligned}$$

Assuming an absorptivity of 1.0 which would be a "worst case" as far as heat load would be concerned, the solar heat load may be calculated as

$$\begin{aligned} q_{\text{solar}} &= \alpha G_i A \\ &= (1.0)(353.6 \text{ BTU/hr ft}^2)(3.37 \text{ ft}^2) \\ &= 1191.6 \text{ BTU/hr} \end{aligned}$$

(2) Convective Heat Loss: the heat loss due to connection to the ambient air may be estimated by

$$q_{\text{conv}} = hA(t_w - T_{\text{amb}})$$

Assuming a value of the convection coefficient equal to 2.0, an area of 10 ft², and an ambient temperature of 100°F (560°R), we have

$$\begin{aligned} q_{\text{conv}} &= (2.0 \text{ BTU/hr ft}^2 \text{ } ^\circ\text{F})(10 \text{ ft}^2)(T_w - 560)^\circ\text{R} \\ &= 20 (T_w - 560) \text{ BTU/hr} \end{aligned}$$

(3) Net Radiation Loss to Ambient: the net radiation loss to the ambient surroundings may be given by

$$q_{\text{rad}} = \epsilon \sigma A F T_w^4 - T_{\text{amb}}^4$$

where

ϵ = surface emissivity = 1.0

σ = Stefan-Boltzmann constant = $0.1714 \times 10^{-8} \frac{\text{Btu}}{\text{hr ft}^2 \text{R}^4}$

A = surface area, $\text{ft}^2 = 10 \text{ ft}^2$

F = view factor to surroundings = 1.0

T_{amb} = ambient temperature = $100^\circ\text{F} = 560^\circ\text{R}$

The radiation loss is therefore

$$\begin{aligned} q_{\text{rad}} &= (1.0) (0.174 \times 10^{-8} \frac{\text{Btu}}{\text{hr ft}^2 \text{R}^4}) (10 \text{ ft}^2) T_w^4 - 560^4 \\ &= (1.714 \times 10^{-8}) T_w^4 - 560^4 \end{aligned}$$

Equating the solar heat load to the sum of the heat losses through convection and radiation and rearranging we get

$$T_w^4 + (1.165 \times 10^9) T_w - (8.21 \times 10^{11}) = 0$$

Solving by trial and error we get the equilibrium surface temperature

$$T_w = 600^\circ\text{R} - 140^\circ\text{F}$$

This represents an increase by a factor of two in the surface temperature; laboratory surface temperature was previously assumed to be 70°F .

Lack of knowledge of the surroundings prevents the above analysis from taking into account reflections from other surfaces. These reflections will tend to increase the radiant load and thereby the equilibrium surface temperature. In an effort to be extremely conservative in the calculation of the heat load, it is assumed that the equilibrium surface temperature is equal to 180°F . An estimate of the heat leak into the container may now be made.

The container selected for use in this application will be filled with liquid nitrogen and will have an interior temperature of -320°F . The container is constructed of aluminum inner and outer vessels with a plastic neck tube. The overall dimensions of a typical vessel would be 24 inches high with an 18 inch outer diameter and a 15.25 inch inner diameter.

The vacuum space between the inner and outer walls is 1.375 inches thick and is filled with Linde Super Insulation. This Super Insulation consists of alternating layers of radiation shields and spacer materials in a high vacuum of 0.1 micron of mercury or lower. Also contained in the vacuum space are Linde Molecular Sieves which adsorb trace amounts of gases that may off-gas from the metal and insulation. A chemical getter is also used to ensure long vacuum life. The thermal conductivity of the Super Insulation is shown in Figure 141. An equation representing these experimental data in the form of the thermal conductivity as a function of temperature is

$$k(t) = (2.2 \times 10^{-5}) + (1.06 \times 10^{-7})(t + 320)$$

This is of the form

$$k(t) = k_o (1 + \beta_o T)$$

Now if

$$T = t + 320$$

$$\text{then } k_o = 2.2 \times 10^{-5}$$

$$\text{and } \beta_o = 0.00482$$

Assuming a simplified model of one dimensional conduction through the super insulation which essentially ignores the losses through the plastic neck tube, the heat transfer rate is given by

$$q = \frac{2\pi k_o}{\ln r_2/r_1} \left(1 + \frac{\beta_o}{2} (T_1 + T_2) \right) (T_1 - T_2)$$

where

$$T_1 = 0 \quad \text{when } t_1 = -320^{\circ}\text{F} \quad \text{case (a)}$$

$$T_2 = 390 \quad t_2 = 70^{\circ}\text{F}$$

$$T_1 = 0 \quad t_1 = -320^{\circ}\text{F} \quad \text{case (b)}$$

$$T_2 = 500 \quad t_2 = 180^{\circ}\text{F}$$

case (a) represents the temperature difference encountered when the outside temperature is 70°F and case (b) is representative of an outside temperature of 180°F. The heat transfer rates for these two cases are given by

$$q_a = \frac{2\pi k_o}{\ln \frac{42}{41}} \left(1 + \frac{\beta_o}{2} (390) \right) (-390)$$

$$q_b = \frac{2\pi k_o}{\ln \frac{r_2}{41}} \left(1 + \frac{\beta_o}{2} (500) \right) (-500)$$

The percent increase in heat transfer due to an increase in exterior wall temperature is given by

$$\% \text{ increase} = \frac{q_b - q_a}{q_a} \times 100$$

This results in the following

$$\% \text{ increase} = \frac{(500 - 390) + \frac{\beta_o}{2} (500)^2 - (390)^2}{500 + \frac{\beta_o}{2} (500)^2} \times 100$$

For $\beta_o = 0.00482$ the percent increase in heat transfer is

$$\% \text{ increase in heat transfer} = 31.5\%$$

The rate of decrease in liquid mass for the 70°F surface temperature was

$$\dot{m} = 0.037 \frac{\text{lbm}}{\text{Hr}}$$

and the corresponding heat transfer was

$$q = 3.157 \frac{\text{Btu}}{\text{Hr}}$$

The increase of 31.5% would indicate a heat transfer rate of

$$q = 4.122 \frac{\text{Btu}}{\text{Hr}}$$

which would indicate a new rate of decrease of mass of

$$\dot{m} = 0.0483 \frac{\text{lb m}}{\text{Hr}}$$

Comparing this calculation with those previously discussed indicates that the time elapsed before refill becomes necessary decreases from 45 days to 40 days. This, of course, is a decrease of 5 days due to the unfavorable ambient conditions.

As can be seen, the logistics problems can be an important consideration. If very high sensitivity is not as important as the logistics problems involved in cooling with liquid nitrogen on a remote platform, then selecting PbSe as the detector material might be best. It is only necessary to cool PbSe to 195°K, which can be accomplished with a thermoelectric cooler (TEC). A discussion of one particular TEC for cooling a detector to 178°K is discussed in the following paragraphs.

The TEC has the following advantages when the heat load is small and the required detector temperature is between 150° and 200°K:

- No moving parts
- Low maintenance
- High reliability
- No consumable gases
- All electric operation

Efficient use of TEC requires consideration of three design factors. Parasitic heat loads must be minimized, cascading of cooler stages must be optimized for best thermal and electrical efficiencies, and a high-conductance heatsink should be used to dissipate the heat rejected by the base of the thermoelectric cooler.

These factors have been optimized for the 3- to 5-micron PbSe detector, resulting in a six-stage cascaded TEC design using a natural convection heatsink. Nominal cooler operation will provide a detector temperature of 178°K at an ambient temperature of 80°F, with an input power of 25 watts.

The performance of a TEC depends on many internal parameters (including materials, geometry, and number of stages) and operational parameters (power input, total thermal load, heatsink temperature, environment, etc). These considerations have been carefully developed by Click and Marlow.

The cooler is derived from the nine-stage cooler previously developed for the Night Vision Laboratories by Nuclear systems Incorporated (NSI) of Garland, Texas. The load and temperature requirements can be obtained by using the lower six stages of the 145°K cooler previously developed by NSI.

The cooler and vacuum enclosure are shown in Figure 142. A low-emissivity shield surrounds the cooler to minimize radiation loading of the cascaded stages. Constantan conductors are used to minimize the thermal conduction load from the detector leads. Performance characteristics of this cooler are shown in Figure 143. The basic cooler specifications are listed in Table 18.

TABLE 18. BASIC COOLER SPECIFICATIONS

<u>Size</u>	
Base	1.0 by 1.0 inch
Height	0.6 inch
Top	0.25 by 0.40 inch
Weight	20 grams
T _{ambient}	300°K
Hot side (T _H)	333°K nominal (on heatsink)
Cold side (T _C)	178°K nominal
Power	25 watts
Voltage	6 volts
Current	4.2 amperes
Heat load (detector)	50 milliwatts

The heatsink must be designed to efficiently transfer heat rejected by the TEC to the air. Two basic types of heatsinks have been considered for use with the six-stage TEC, assuming that the ambient air temperature will vary from 40° to 120°F. Both natural-convection and forced-convection heatsinks have been evaluated, and the calculated performance curves are shown in Figure 144. A weight restriction of 1 pound maximum was placed on both heatsinks. Each is of the highest efficiency possible within the weight and volume constraints of the system.

The forced-convection unit would provide a 10°K lower detector temperature than the natural-convection unit. However, it would require additional power for a 10-cubic-feet-per-minute capacity blower, would weigh 1 pound, would

substantially increase the acoustical noise, and would introduce forced vibrations to the components. The natural-convection heatsink would be slightly larger, but would weigh only 12 ounces and be totally passive in operation.

The heat dissipation capability of the natural-convection heatsink is limited by fin surface area rather than internal thermal conduction. Therefore, this type could be fabricated of aluminum instead of a material with a higher thermal conductivity without loss in heat dissipating efficiency. This natural-convection heatsink is proposed for use on the 3- to 5-micron PbSe detectors.

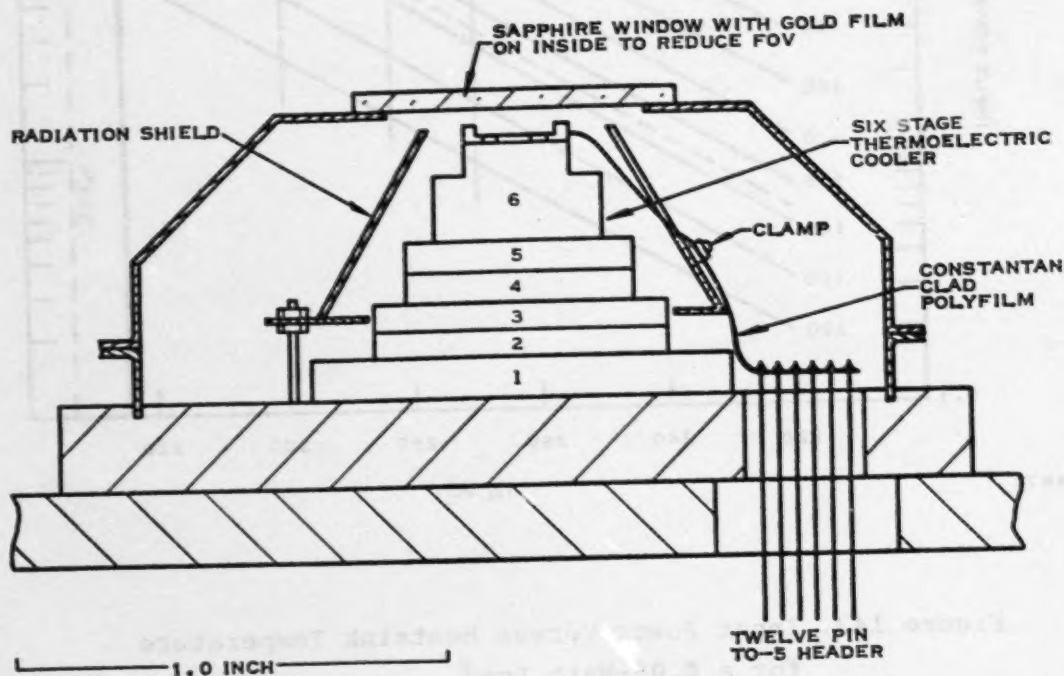


Figure 142. Schematic of Proposed Thermoelectric Cooler

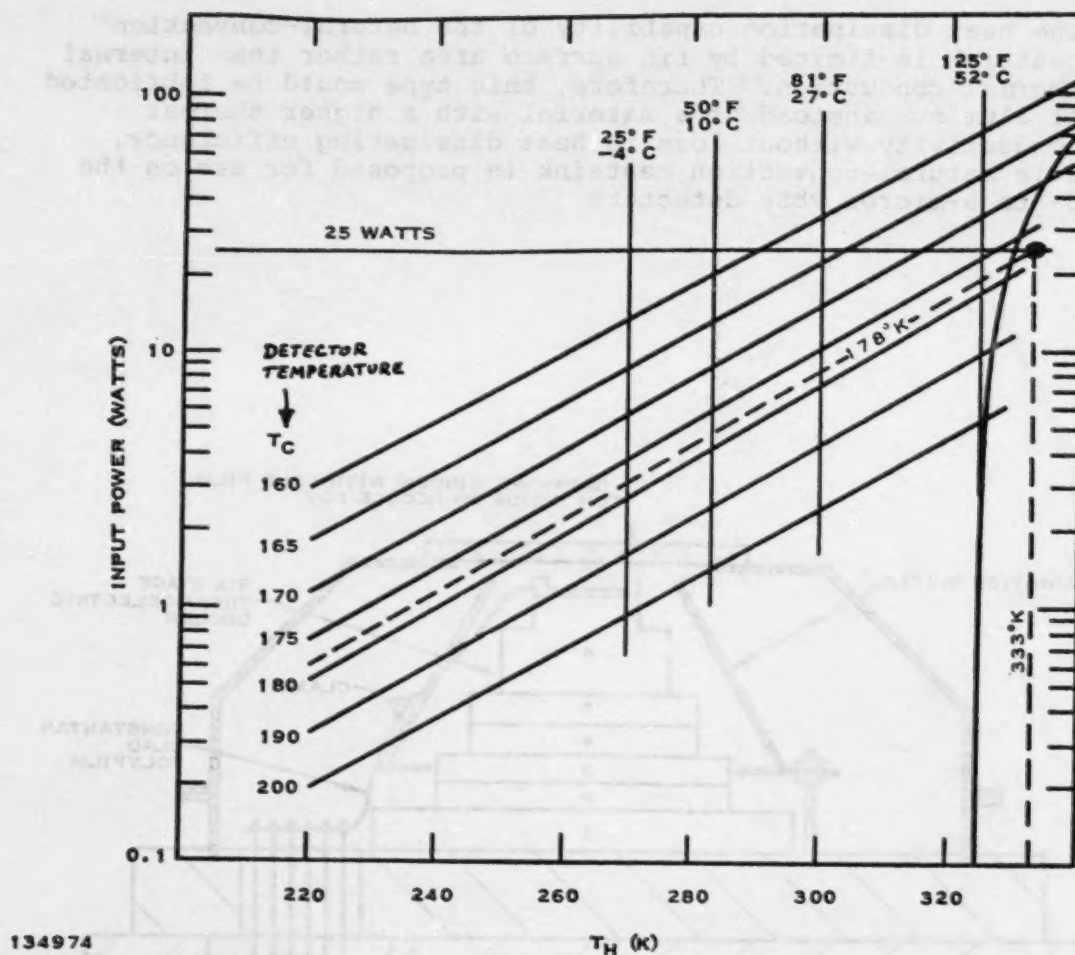


Figure 143. Input Power Versus Heatsink Temperature
for a 0.05-Watt Load

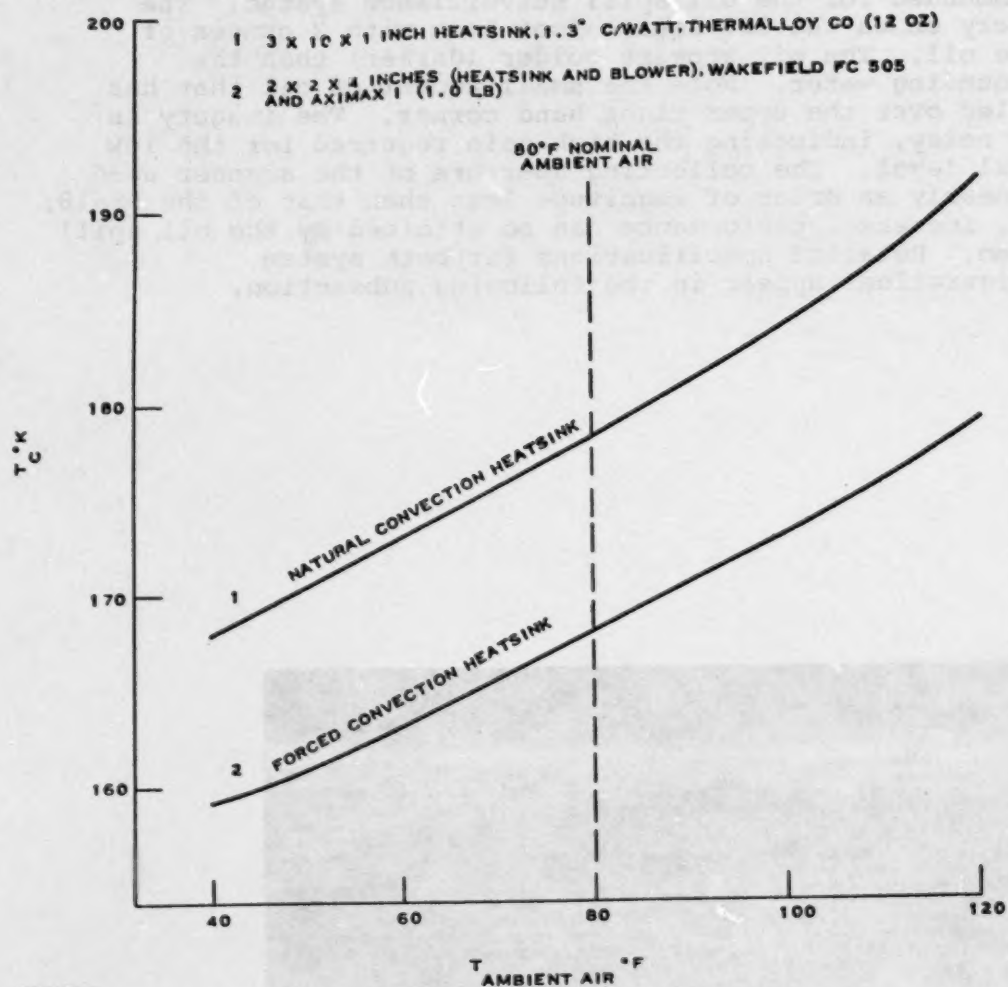


Figure 144. Cold Side Temperature Versus Hot Side Temperature for a 0.05-Watt Load and 25-Watt Input Power

If sensitivity is of primary importance, the HgCdTe detector is recommended. If alleviating logistics problems is of primary importance, the PbSe detector is then recommended.

Tests conducted using a 3- to 5.5-micron scanner as a part of this program has verified the principle. Figure 145 shows imagery made at 2200 hours at the oil spill test facility with a line scanner and recorded on photographic film as is recommended for the oil spill surveillance system. The imagery shows the 100-square-foot boom with 2 ounces of crude oil. The oil appears colder (darker) than the surrounding water. Note the small amount of oil that has spilled over the upper right hand corner. The imagery is very noisy, indicating the high gain required for the low signal level. The collecting aperture of the scanner used was nearly an order of magnitude less than that of the RS-18; thus, increased performance can be attained by the oil spill system. Detailed specifications for both system configurations appear in the following subsection.

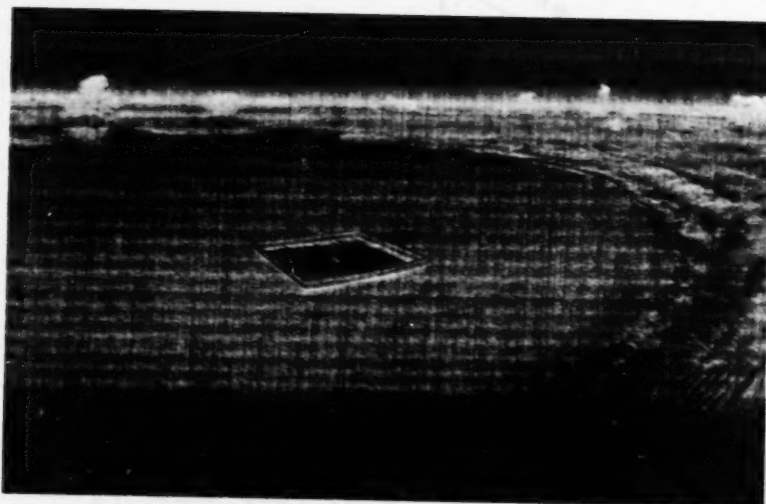


Figure 145. Oil Spill Imagery, 3- to 5.5-Microns

The nature of semiconductor detectors is such that a tradeoff exists between spatial and thermal resolution capability. It is suggested that the spatial resolution for the oil spill sureveillance system be 3 to 5 milliradians. This will yield maximum thermal sensitivity. A 3-milliradian system will resolve 3-foot targets at a range of 1000 feet which should be sufficient for most applications.

Technical Specifications

The RS-18 is a reflective optics system utilizing a single-sided rotating wedge mirror for scanning and Cassegrainian collecting optics. The collecting optics, consisting of a 3.5-inch-diameter parabolic primary mirror and a 1.4-inch diameter flat secondary mirror, are mounted in an optical tube making the converging optics modular in nature. The primary is three-point mounted at one end of the tube, and the secondary is mounted on a three-finger aluminum spiker attached at the opposite end. Radiation baffling is incorporated into the tube assembly. One baffle is provided around the secondary mirror, and the other is located on the detector assembly surrounding that portion of the detector assembly passing through the primary. This baffling is necessary to prevent extraneous radiation from reaching the detectors without first going through the system scanning optics. The collecting optics mounting arrangement has been proven on existing systems to provide a very rugged and structurally rigid optical assembly. Once elements of the converging optics assembly are mounted, the assembly is slipped into the scanner housing. The optical tube provides support and rigidity to the scanner housing itself. The system effective aperture is 7.7 square inches. This gives a system f/number of 1.93.

As discussed in the previous paragraphs, two different detectors are suggested for operation in different applications. The primary detector choice is HgCdTe cooled to 77°K using liquid nitrogen. The secondary choice, for applications where the requirement for liquid nitrogen is prohibitive, is a PbSe detector thermoelectrically cooled to 195°K.

Each interchangeable detector assembly consists of a Dewar (thermoelectric cooler for PbSe), detector, and preamplifier. The preamplifier is a linear, ac-coupled, high-gain, low-noise amplifier matched to the detector impedance to provide a detection-noise limited system. The video electronics does not have any function that can irreversibly alter the quantitateness of the data. The raw video signal from the preamplifier is ac coupled into the video post-amplifier where the portion of the video corresponding to a heated calibration source is clamped to a variable dc voltage.

This voltage may be set manually or automatically to vary with changes in the temperature of the surrounding water surface using an in situ temperature sensing element in the water. The purpose of the automatic mode is to provide a constant output level corresponding to water irregardless of diurnal or seasonal water temperature variations.

The calibration source is provided to permit qualitative temperature data to be obtained. A calibrated temperature analog voltage will be provided for monitoring with a readout range of -25°C to $+30^{\circ}\text{C}$ and an accuracy of $\pm 0.4^{\circ}\text{C}$. The readout temperature is obtained from two linear platinum-wire temperature sensors embedded at the base of the blackbody to sense the contact temperature of the source. The sensors are used in a low-power bridge circuit to accurately measure the source temperature. A low-drift dc amplifier is then used to provide a dc temperature analog voltage of approximately $0.1 \text{ volts}/^{\circ}\text{C}$.

The active area of the calibration source measures 4 by 5 inches and is located 2.5 inches from the scan mirror axis. With the above size and spacing, the IFOV of each source will dwell 60 resolution elements before vignetting occurs. This dwell corresponds to 9 degrees of scan per revolution. The heated blackbody calibration source is mounted above and to one side of the scan mirror. Temperature sensing and heating elements are mounted in the base of the blackbody source. Effective emissivity of the source is better than 0.99. Experiments performed have resulted in measured emissivities of greater than 0.993.

The effect of this video system is to achieve a dc-coupled system without its disadvantages, such as dc level shift with the changing temperature of the electronics and dc level shift due to changing background radiation seen by the detector because of Dewar window temperature changes.

A common parameter of IR systems, used to measure their temperature sensitivity, is noise equivalent temperature (NET). NET is defined as that temperature difference which produces a unity signal-to-noise ratio out of the system. The NET of the oil spill surveillance scanner may be mathematically determined from the following equation:

$$\text{NET} = \frac{\pi (f.l) (\Delta f_n)^{1/2}}{4\sigma \epsilon T^3 A_o (\Delta \theta \Delta \phi)^{1/2} D^* \tau_a \tau_o r}$$

where

- $f.l$ = optical focal length
- Δf_n = noise bandwidth = $\pi/2$ B.W.
- σ = Stefan-Boltzmann constant
- ϵ = target emissivity
- T = temperature of target in $^{\circ}K$
- A_o = area of optical aperture
- $\Delta\theta$ = across-track instantaneous field of view
- $\Delta\phi$ = along-track instantaneous field of view
- D^* = detectivity of the detector normalized for unity bandwidth and detector area
($cm-Hz^{1/2} - watt^{-1}$)
- τ_a = transmission of the atmosphere
- τ_o = transmission of the optical system
- r = system response to input (γ is unity for large target NET calculations or the MTF of the system for resolution size targets)

Under worst case conditions, the NET has been calculated for each detector type. The system configuration was assumed to be 3-milliradian resolution ($\Delta\theta-\Delta\phi$) with a scan speed of 100 scans per second for HgCdTe and 5 scans per second for PbSe. The 5 scans per second rate is maximum for PbSe in a 3-milliradian configuration due to the relatively low frequency response of the detector. The system NET is specified to be:

$$\begin{aligned} NET_{HgCdTe} &\leq 0.1^{\circ}C \\ NET_{PbSe} &\leq 0.25^{\circ}C \end{aligned}$$

In practice, the scanner NET is determined by the following procedure. Two known temperature targets are scanned by the receiver and their temperature difference ($\Delta T = T_2 - T_1$) is noted. The peak-to-peak signal output (ΔS) produced by these two targets is measured. At the same point in the electronics chain, the system noise (n) is determined by use of a true rms voltmeter. A signal-to-noise ratio for the two targets is then calculated ($\Delta S/N$). This number is then divided into the temperature differential of the two targets to calculate NET or

$$NET = \frac{\Delta T}{\Delta S/N}$$

SECTION XI

TOTAL SYSTEM APPROACH

The sensors tested in this study program can provide oil spill surveillance for estuaries, rivers, drainage channels, bridges, docks, offshore drilling platforms, and onshore or offshore separator facilities. For each application there is a particular mix of passive and active sensors that provides the best cost-effective oil spill surveillance.

For short range staring applications the MOD2 active sensor, described in Section IX, provides adequate low-cost surveillance. Conversely, the active sensor does not have the range to cover a large bridge area; therefore, the passive sensor in a line scan mode should be used.

One of the more challenging surveillance applications is the oil separator. Here the need for an unmanned alarm system is important due to the large number of both offshore and onshore installations which have continuous water output. Figure 146 shows a schematic representation of a separator. Many offshore wells feed a single offshore separator platform. The oil and water from the wells is separated and the oil is then transmitted by pipe to the onshore station. The water emitted from this offshore separator can contain oil droplets that immediately rise to the surface and form a detectable sheen. The existence of this sheen can be monitored by the active sensor.

The final separation of oil and water is performed at the onshore facility as indicated in Figure 146. In this case the water output from the separator station enters the public supply by means of a channel as shown in Figure 147. An active or passive sensor, depending on the size of the channel and the point in the channel where the sensor is located, should be located downstream from the oil skimmers. This would provide detection of any oil not detained by the skimmers.

Examples of sensor versus application are given in Table 19. In addition to the basic sensor, the scan and display types are treated as options. Consider the case of the offshore separator. Here an alarm only would be needed since the application is one of spill prevention as opposed to surveillance and possible legal documentation. The latter would be needed in a river area where total areal extent would be required.

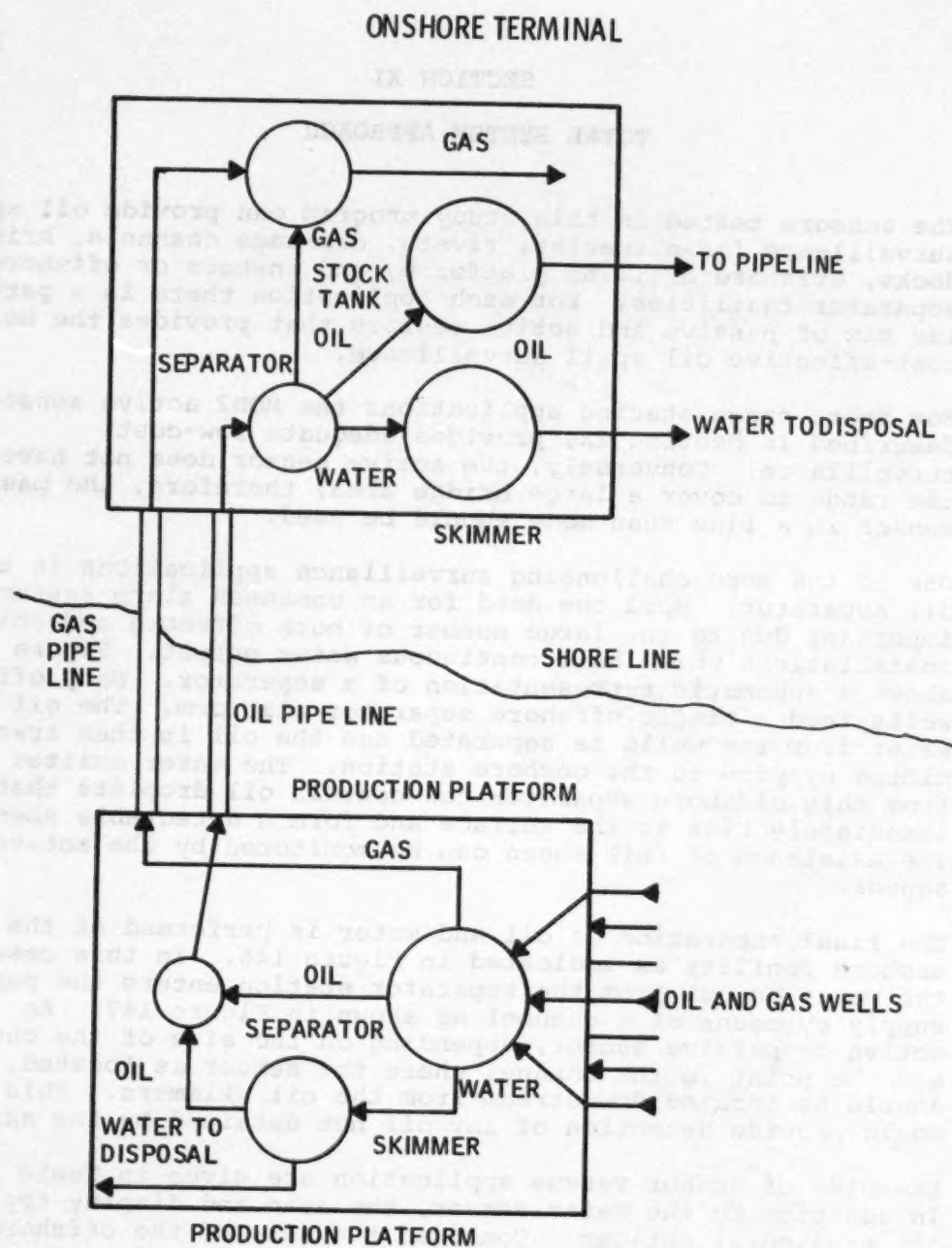


Figure 146. Schematic Representation of an Oil Separator Facility

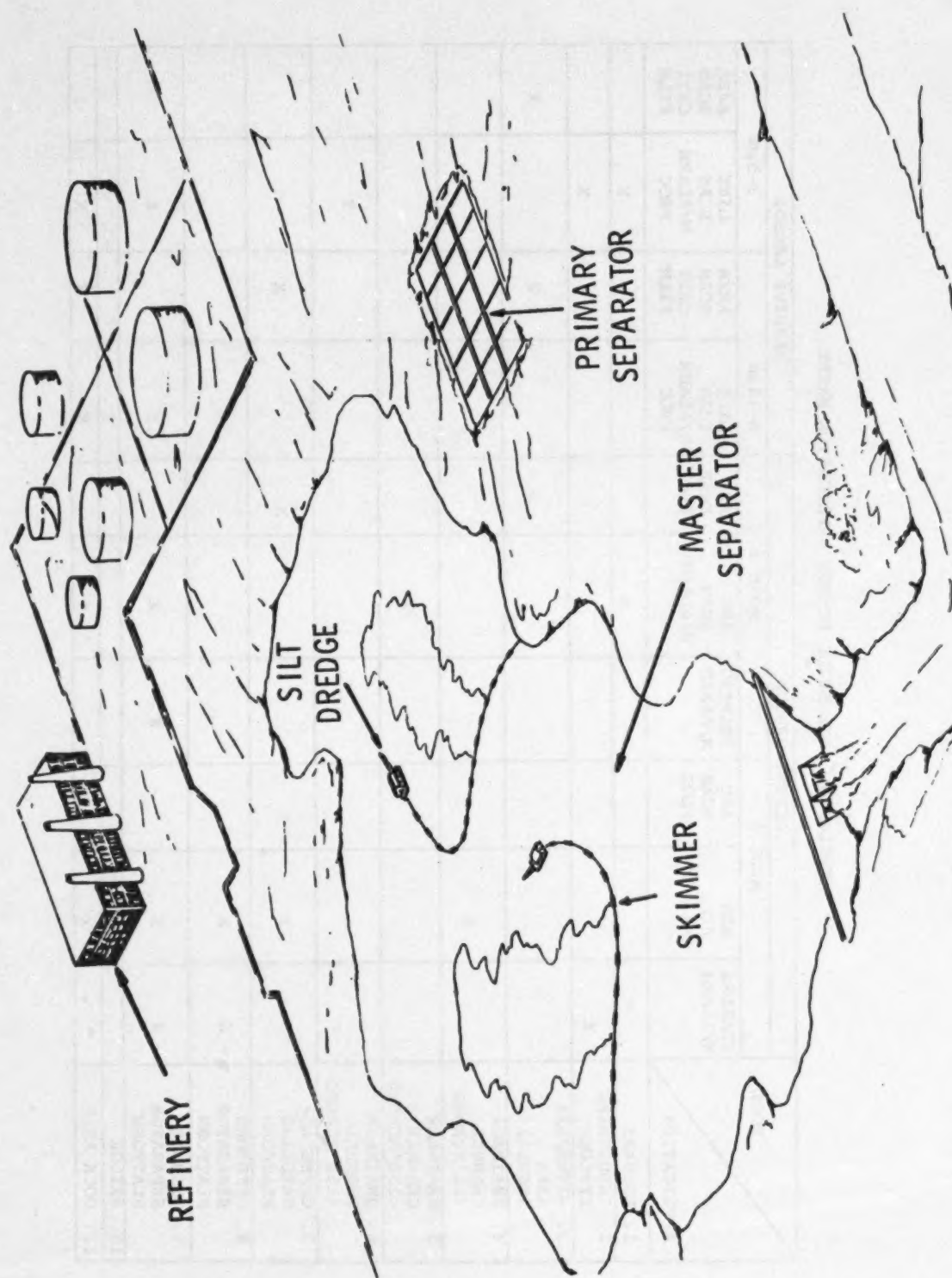


Figure 147. Onshore Oil Separator Facility

TABLE 19. OIL SPILL SENSOR APPLICATION MATRIX

MODE APPLICATION	ACTIVE SENSOR					PASSIVE SENSOR				
	MODE 2		MODE 3			8-14 μ m		3-5 μ m		
	STARTING W/ALARM	ARC SCAN W/ALARM	ARC SCAN PLOT	STARTING W/ALARM	ARC SCAN W/ALARM	ARC SCAN PLOT	LINE SCAN W/ALARM PROC	AREA SCAN CRTL FILM	LINE SCAN W/ALARM PROC	AREA SCAN CRTL FILM
1. ESTUARY					X				X	
2. INDUSTRIAL EFFLUENT	X								X	
3. RIVER/BAY AREA (TOWER)								X		X
4. DRAINAGE CHANNEL <60' ACROSS		X								
5. DRAINAGE CHANNEL <150' ACROSS			X							
6. DRAINAGE CHANNEL >150' ACROSS									X	
7. OFFSHORE DRILLING PLATFORM		X	X					X		
8. OFFSHORE SEPARATOR PLATFORM	X	X					X			
9. ONSHORE SEPARATOR PLATFORM	X	X		X	X		X		X	
10. BRIDGE							X			
11. DOCK AREA		X			X		X	X	X	X

The sensor configuration, depending on the particular application, can be expensive. However, when mass produced, most sensor configurations would be low cost.

SECTION XII

ACKNOWLEDGEMENTS

Grateful acknowledgement is given to Pat Daly and Bill Hawley of Night Vision Laboratory for granting Texas Instruments permission to use the MIRS system and release the imagery for publication.

Hugh Yantis of Texas Water Quality Board, Major General H.R. Parfitt of the Southwest Division Corps of Engineers, and Bill Aston of Dallas Power and Light have our thanks for their assistance in trying to find a suitable test site.

The assistance of Professor M.A.Collin, Professor R.L. Simpson and Professor W.G.Wyatt, of Southern Methodist university in the search of a local test site is acknowledged with thanks.

The advice of Dr. Tim Matzke and Dr. Oppenheimer of the Environmental Protection Agency on legal limits of oil spilling for research purposes is greatly appreciated.

Ray Lozano, Dick Peckham and Jerry Thornhill of the EPA were very helpful in advising us on particular applications of oil spill sensors.

Jerome Overfield of Pollution Abatement Research is acknowledged for his consultation.

The contribution of various samples of oil from Humble, Sun, and Richfield Oil Companies is greatly appreciated.

The support of John Riley of the EPA is acknowledged with much thanks.

SECTION XIII

REFERENCE

1. Albert V. Jelalian, "Sea Echo at Laser Wavelengths", Proceedings of the IEEE, Vol. 56, No. 5, May 1968.
2. JOSA, "The Refractive Index of Liquid Water in the Near Infrared Spectrum", Melchor Centeno, Vol. 31, p 244, 1941.
3. Born and Wolf, Principles of Optics, Pergamon Press, 3rd Edition, pp 90-98.
4. H. W. Yages, The Absorbtion Spectrum From 0.5 to 25 Micron of a 1000-Foot Atmospheric Path at Sea Level, Naval Research Laboratory, September 1957.
5. J. L. Emmett, A. L. Showlow and E. H. Weinburg, "Direct Measurement of Xenon Flashtube Opacity," Journal of Applied Physics, Vol. 35, No. 9, September 1964, pp 2601-2604.
6. John H. Gonca and P. Bruce Newell, "Spectra of Pulsed and Continuous Xenon Discharges", Journal of Optical Society of America, Vol. 56, No. 1, January 1966, pp 87-92.
7. V. W. Forsythe, "Measurement of Radiant Energy", McGraw-Hill, N.Y. 1937.
8. Journal of Geophysical Research, March 15, 1965, Vol. 70, No. 6, pp 1334.

SECTION XIV

GLOSSARY

Active IR System - the infrared energy used to provide target illumination is generated internal to the system.

Angular Scan Capability - range of angles from azimuth for effective signal reception.

Anomalous Dispersion Curve - graph of change in reflectivity as a function of wavelength in the region of a resonant absorption.

Areal Coverage - coverage of an area.

Azimuth - vertically downward.

Bistatic Reflection - reflectance measurements where the optical paths of the transmitter and receiver are not congruent.

Blackbody - a solid that radiates or absorbs energy with no internal reflection of the energy at any wavelength.

Chopping - interrupting a current or a light beam at regular intervals for purposes of modulation.

C-H Resonance - vibrational frequency of carbon-hydrogen element in a molecule.

Detector - a device that produces an electrical output that is a measure of the radiation incident on the device.

Diffuse - rough surface.

Estuary - an inlet or arm of the sea, the wide mouth of a river, where the tide meets the current.

(FOV) Field Of View - the solid angle from which objects can be acceptably viewed, photographed, or otherwise detected.

f/Number - a ratio of focal length to aperture opening.

Heterodyne Detection - combining the received signal with a locally generated wave to produce sum and difference frequencies (demodulation)

Imagery - view of objects of interest stored on film, tape, or other types of storage material.

Infrared (IR) - a form of electromagnetic radiation, at a frequency lower than visible light, and generated by thermal agitation.

Lambertian Surface - totally diffuse

Microphonic Noises - noises due to magnetic shock or vibration.

MOD 1 - active system used in test section with reflective optics and a 400 Hz modulated tungsten beam.

MOD II - active system used in test section with refractive optics and 400 Hz modulated tungsten beam.

MOD III - active system used in test section with a pulsed Xenon arc source rather than a 400 Hz modulated tungsten beam.

O-H Resonant Mode - the mode of vibration of the oxygen-hydrogen element of a molecule.

Passive IR System - the infrared energy used to produce target illumination is generated external to the system.

Real Time Presentation - presentation generated fast enough to be viewed at the same time the system is pointing toward subject.

Reflectance - light or heat bouncing back toward the source

Resonance Absorbption - an absorbption which occurs due to a fundamental vibrational mode in the material.

Sensor - image detecting system

Slick - A layer of oil floating on water.

Signal-To-Noise (S/N) - ratio of magnitude of the signal to that of the noise

Skin Depth - the depth at which the radiation is $1/e$ times the radiation of the surface.

Spectral - pertaining to the frequency or wavelength aspect of a signal.

Specular - like a mirror surface

Staring System - system which has a single resolution element which is not scanned in any direction.

Subsurface Effects - effects of physical variations beneath the surface of the water on signal to be detected on the surface.

Thermoelectric Cooler (TEC) - a device used to cool infrared detectors. The mechanism for cooling is electric current passing through a series of diodes in such a way as to heat one side of the device and cool the other. Peltier cooler.

Wide Band IR Pulse - an electromagnetic pulse in the infrared region of the spectrum which consists of a wide range of frequencies.